PB83-149088

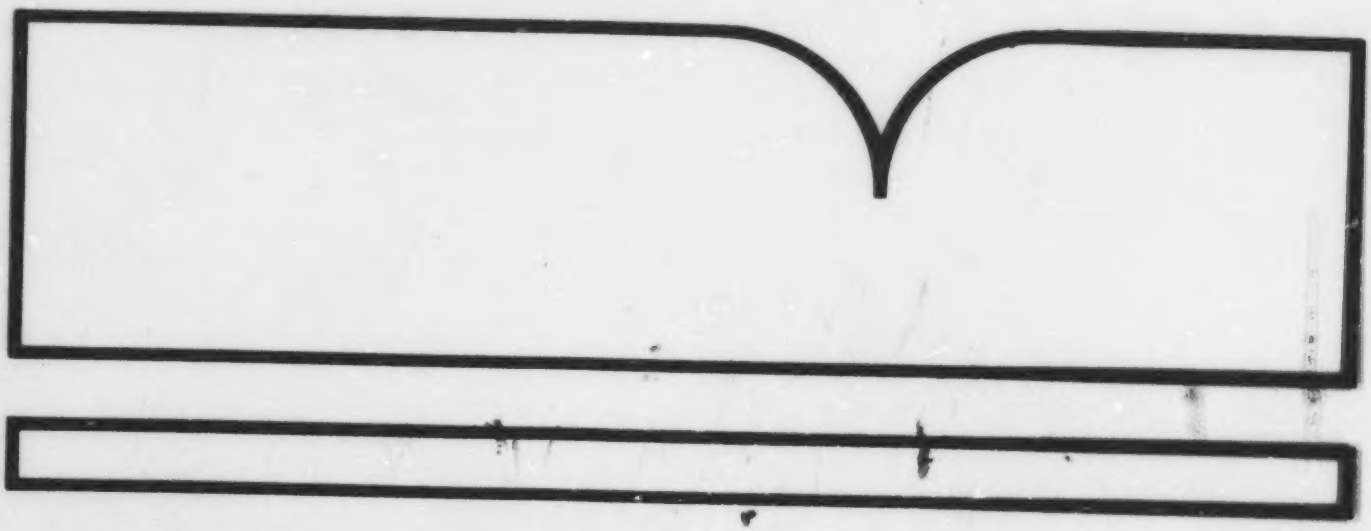
# Determination of Explosion Venting Requirements for Municipal Solid Waste Shredders

Factory Mutual Research Corp.
Norwood, MA

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Dec 82



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| TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing) | | |
|---|---|---|
| 1. REPORT NO. EPA-600/2-82-102 | 2. | 3. RECIPIENT'S ACCESSION NO. PB83 149088 |
| 4. TITLE AND SUBTITLE DETERMINATION OF EXPLOSION VENTING REQUIREMENTS FOR MUNICIPAL SOLID WASTE SHREDDERS | | 5. REPORT DATE December 1982<br>6. PERFORMING ORGANIZATION CODE |
| 7. AUTHOR(S) Robert G. Zalosh, John P. Coll | | 8. PERFORMING ORGANIZATION REPORT NO. |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS Factory Mutual Research Corporation 1151 Boston-Providence Turnpike Norwood, Massachusetts 02062 | | 10. PROGRAM ELEMENT NO. BRD1A<br>11. CONTRACT/GRANT NO. 68-03-2880 |
| 12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin.,OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268 | | 13. TYPE OF REPORT AND PERIOD COVERED Final (Sept. 1979-Sept. 1981)<br>14. SPONSORING AGENCY CODE EPA/600/14 |
| 15. SUPPLEMENTARY NOTES Project Officer: Carlton C. Wiles, 513/684-7871 | | |

16. ABSTRACT

A gas explosion test program has been conducted in a realistic full-scale mock-up of a municipal solid waste shredder. The 2200-ft$^3$ (61 m$^3$) mock-up simulates a horizontal-shaft hammermill (including rotating shaft, discs, and hammers, but without trash) with a large inclined feed hood. Varying amounts of propane have been injected into the shredder and the resulting gas concentrations generated by rotor-induced mixing have been measured. Eight propane explosion tests have also been conducted with varying volumes of near-stoichiometric propane-air mixtures and various hammermill shaft speeds. Test results indicate that venting through the top of the shredder effectively keeps pressures under 6 psig (41 kPa) at shredder shaft speeds of 250-660 rpm and 16 hammers, but allows pressures to reach 10-15 psig (69-103 kPa) at a shaft speed of 900 rpm with 48 hammers.

The pressures generated with a hammermill shaft speed of 900 rpm and 48 hammers are much larger than would have been expected on the basis of current explosion venting design guidelines. New guidelines are suggested which include a quantitative relationship between peak pressure and shaft speed. The recommended guidelines also discuss the effects of vent ducting, vent covers, and blast waves emitted during a shredder explosion.

This report was submitted in fulfillment of Contract No. 68-03-2880.

| 17. KEY WORDS AND DOCUMENT ANALYSIS | | |
|---|---|---|
| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
| | | |
| 18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC | 19. SECURITY CLASS (This Report) UNCLASSIFIED<br>20. SECURITY CLASS (This page) UNCLASSIFIED | 21. NO. OF PAGES 56<br>22. PRICE |

EPA Form 2220-1 (9-73)

PB83-149088

EPA-600/2-82-102
December 1982

# DETERMINATION OF EXPLOSION VENTING REQUIREMENTS FOR MUNICIPAL SOLID WASTE SHREDDERS

by

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Contract No. 68-03-2880

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CINCINNATI, OHIO 45268

EPA Form 2390-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 287)
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## FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This particular research project was motivated by suggestions, solicited by EPA, from the American Society for Testing and Materials E38.07 Subcommittee on the Health and Safety Aspects of Resource Recovery. The Subcommittee is also assisting EPA in disseminating project results among relevant users in the solid waste processing industry.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

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## ABSTRACT

A gas explosion test program has been conducted in a realistic full-scale mock-up of a municipal solid waste shredder. The 2200-$ft^3$ (61 $m^3$) mock-up simulates a horizontal-shaft hammermill (including rotating shaft, discs, and hammers, but without trash) with a large inclined feed hood. Varying amounts of propane have been injected into the shredder and the resulting gas concentrations generated by rotor-induced mixing have been measured. Eight propane explosion tests have also been conducted with varying volumes of near-stoichiometric propane-air mixtures and various hammermill shaft speeds. Test results indicate that venting through the top of the shredder effectively keeps pressures under 6 psig (41 kPa) at shredder shaft speeds of 250-660 rpm and 16 hammers, but allows pressures to reach 10-15 psig (69-103 kPa) at a shaft speed of 900 rpm with 48 hammers.

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## ACKNOWLEDGMENTS

The authors would like to acknowledge the support and cooperation of Mr. Carlton Wiles, EPA Technical Project Officer for this contract.

Advice on the design of the shredder mock-up was provided by the ASTM E38.07 Subcommittee on Health and Safety Aspects of Resource Recovery. Dr. Joseph Duckett, Chairman of the Subcommittee, has been particularly helpful at several key stages in the project.

Finally, the authors would like to formally thank the FMRC Test Center Staff for their assistance in building and repairing the mock-up, and for carrying out the various tests.

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# SECTION 1

## INTRODUCTION

In recent years, shredding has become a common processing step prior to the land disposal, resource recovery or incineration of municipal solid waste (MSW). The refuse throughput rate entering these MSW shredders is often too large to permit thorough screening of the input stream to remove all dangerous materials. Consequently, potentially explosive materials, such as gasoline, propane, paint thinner/cleaner, gunpowder, etc., occasionally enter the shredder. Impact sparks or hot spots generated during shredding (hammering) can ignite these materials and cause an explosion. In the time interval 1971 to 75 there were approximately 100 reported[1,2] shredder explosions resulting in property damage or injury. No formal tally of explosions has been conducted since 1975, but it is clear that explosions continue to plague MSW shredding plants[3].

As a result of these explosions, shredder manufacturers and operators have started implementing traditional protection measures for industrial explosion hazards. The most popular of these protection measures is explosion venting. The basic explosion venting concept is to allow an incipient pressure rise to actuate blowout panels or curtains so as to vent unburnt gas and combustion products before damaging pressures develop in the enclosure (shredder). To be effective, the vent deployment pressure, area, and location, must accommodate the volume generation rate of gaseous combustion products. Thus, a particular vent configuration may be less effective for rapid combustion explosions than for relatively slow explosions. In the extreme case of a detonation, i.e., supersonic flame propagation, explosion venting would be totally ineffective. Fortunately, the overwhelming majority of shredder explosions have been deflagrations, i.e., subsonic flame propagation, and are, therefore, amenable to some form of explosion venting[1,2].

Existing explosion venting design criteria[4] are based on tests with simple structures such as rooms or spherical or cylindrical pressure vessels. MSW shredders represent a more severe explosion environment because of the effects of rotor windage/turbulence and internal obstructions (shaft, hammers, breaker plates, trash, etc.). These effects increase the rate of combustion and thereby escalate the rate of pressure rise. In addition, peripheral equipment, such as inlet hoods and exhaust ducting, can reduce vented gas flow rates to further reduce venting effectiveness. Consequently, existing explosion venting guidelines may not be adequate for the more challenging shredder explosion applications.

Prior to the project, the only existing explosion test data for shredders were obtained for dust explosions[5] in a nonoperating shredder. However,

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most accidental shredder explosions are now known[1,2] to be caused by flammable gases and vapors, which usually have much faster burning velocities than combustible dusts. Furthermore, it is important to account for rotor-induced turbulent gas combustion rates in order to realistically simulate typical accidental shredder explosion conditions.

The objective of the project described here has been to develop and test explosion venting requirements for MSW shredders. The approach has been to perform gas explosion tests in a realistic full-scale mock shredder outfitted with a typical explosion vent configuration employed at several MSW shredding facilities. The need for large-scale testing has been demonstrated by previous test programs[6,7] which indicated a lack of any simple scaling relationship between small-scale and large-scale test results. The MSW shredder mock-up used in the present test program is described in the following section.

## SECTION 2

## SHREDDER MOCK-UP

A full-scale mock-up of a large horizontal shaft hammermill has been constructed at the Factory Mutual Research Test Center in West Glocester, Rhode Island. The mock-up has the approximate size and shape of a Williams 680 shredder. It typifies, albeit slightly larger, most horizontal hammermills in use at MSW shredding facilities across the country. Drawings of the mock-up are shown here in Figure 1. It is 27 ft (8.23 m) high with a total internal volume of 2200 $ft^3$ (62 $m^3$) including a 660 $ft^3$ (19 $m^3$) inclined inlet hood.

As Figure 2 illustrates, the shredder structure consists of a steel frame with 1 1/2-in. (3.8 cm) thick plywood walls. The steel frame and sheet metal clad, plywood wall panels were designed to withstand an internal quasi-static explosion pressure of 5 psig (34.5 kPa) together with thrust loads caused by vented gas. Structural response of the steel frame under these loads was calculated using the Structural Dynamics Research Corporation computer code Static Analysis of General Structures (SAGS). The original frame design was reinforced by additional truss members until the SAGS code indicated that stresses would not exceed the yield stress.

Some of the 4-ft x 4-ft (1.2 m x 1.2 m) plywood panels were fastened with collapsible washer type explosion vent fasteners so that the panels could blow off at a prescribed static overpressure during the explosion tests. The number of deployed panels and the deployment overpressure could be varied in accord with the desired test conditions. In most of the tests, the four panels at the top of the shredder were deployed to simulate the most common venting configuration for actual operating MSW shredders. Besides the 55 $ft^2$ (5.1 $m^2$) vent area provided by this configuration, additional venting capacity was available through the inlet hood and the bottom discharge areas described below.

The hammermill shaft on the mock-up has been outfitted with twenty-four 36-in. (91 cm) diameter 1-in. (2.5 cm) thick plywood discs. Two simulated hammers in the form of 15-in. (38 cm) long aluminum bars can be fastened to each of the discs. In all but the last explosion test, only 16 hammers were installed in order to limit motor torque and horsepower requirements. In the last test, all 48 hammers were installed. The plywood discs and aluminum hammers in the shredder can be seen in Figure 3, a photograph of the lower portion of the mock-up before the panels on the front face were installed.

Most of the tests were conducted with a 3-hp (2.2 kW) motor driving the shaft via a variable speed drive unit to generate shaft speeds in the range

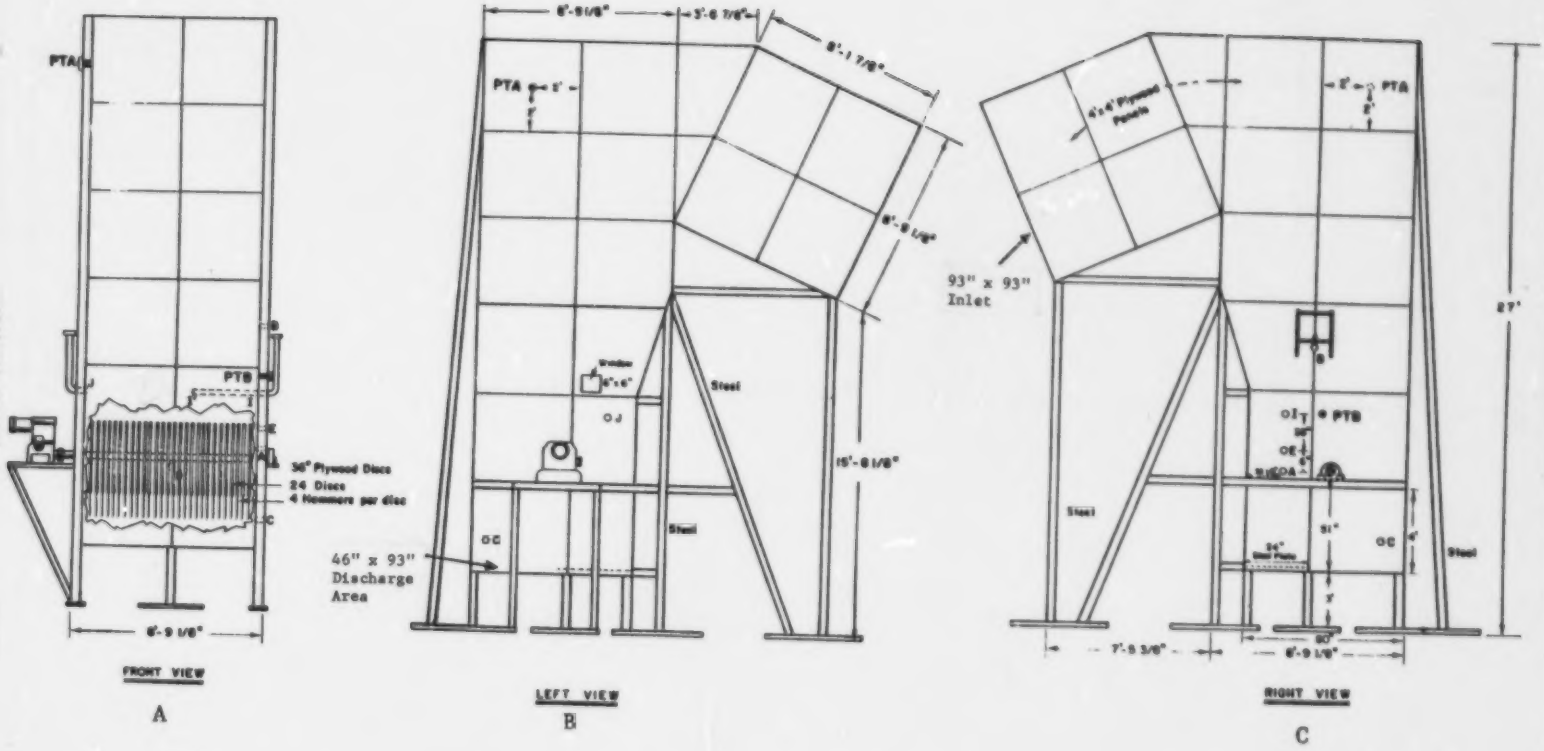


Figure 1. Shredder mock-up

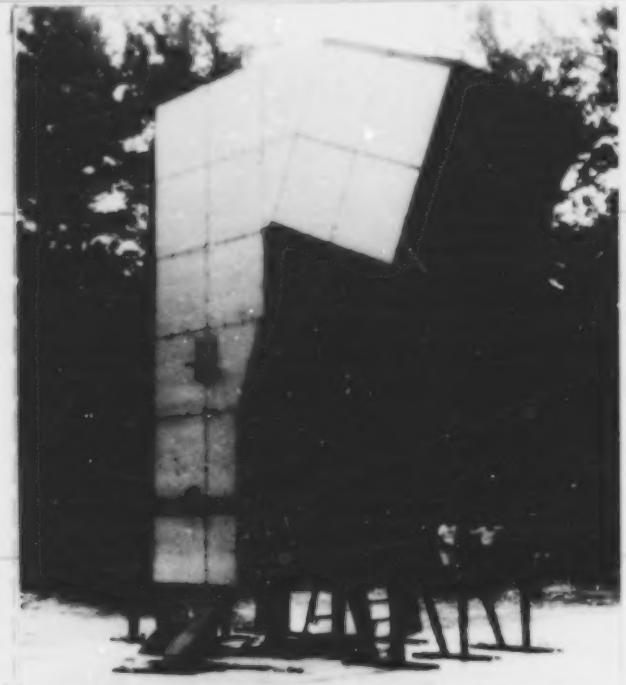

Figure 2. Shredder mock-up at test site

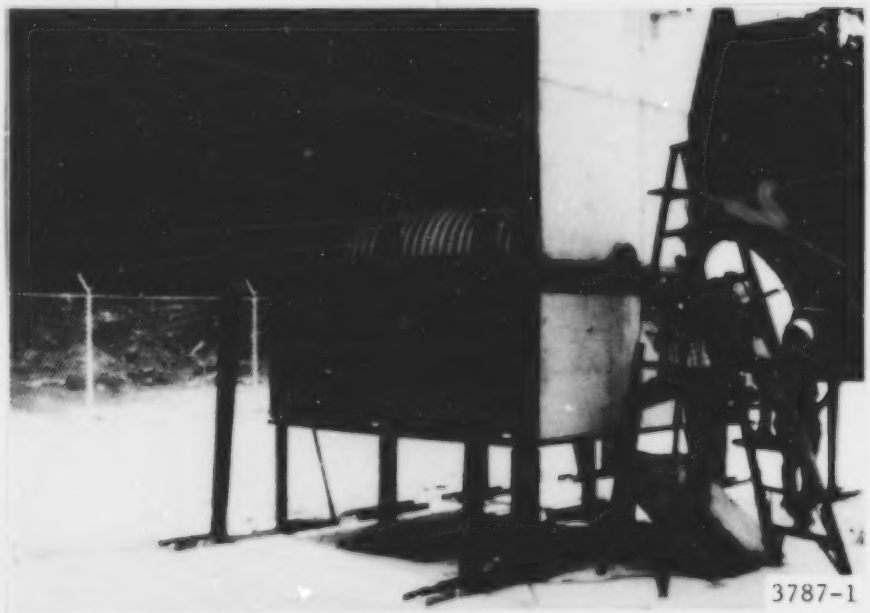


Figure 3. Hammermill inside shredder mock-up

250 to 690 rpm. In the last explosion test, the 3-hp motor was replaced by a 30-hp motor with a fixed speed transmission driving the shaft at 900 rpm.

Although there are no inlet or discharge conveyors, the discharge area of the shredder mock-up is designed to be representative of typical MSW shredder installations. There is a semi-cylindrical steel grating in the 46-in. x 93-in. (117 cm x 236 cm) discharge area at the bottom of the shredder, which is 3 ft (0.91 m) above the concrete test pad on which the shredder is constructed. The confinement associated with this configuration simulates the discharge conveyor section under an operating MSW shredder.

No attempt has been made to put any trash throughput into the shredder mock-up. By obstructing inlet and discharge areas, trash throughput in a real MSW shredder may affect the combustible gas accumulation process prior to an explosion and vented gas flow rates during the explosion. This has been simulated in the mock-up by covering the 59 $ft^2$ (5.5 $m^2$) inlet area and the 29.7 $ft^2$ (2.76 $m^2$) discharge area with polyethylene sheets in many tests.

Trash throughput would also affect the combustion rate. It is impossible to tell by how much the trash throughput might affect the rate of pressure rise. However, the authors feel that the net effect of trash throughput would be to lower the rate of pressure rise, because the heat sink effect of the trash would probably be more significant than any additional turbulence caused by the trash in the already turbulent shredder environment. It would be helpful at some later date to confirm this speculation with explosion tests in an actual operating MSW shredder.

## SECTION 3

## GAS MIXING AND FLOW VISUALIZATION TESTS

Prior to the explosion tests, flow visualization and gas mixing tests were conducted to determine how flammable gas-air mixtures might form during a typical shredder explosion scenario. The scenario involves an intact flammable vapor container being input to the shredder and being broken by hammer impact. Flammable vapor released from the broken container is diluted by the rotor-induced air flow. Flow visualization tests were designed to reveal induced air flow patterns causing gas dilution. The gas mixing tests were designed to determine the spatial and temporal extent of flammable gas-air mixtures formed during this scenario.

### INDUCED FLOW PATTERNS

The flow visualization tests consisted of lighting a chemical smoke candle placed near the hammermill shaft and then observing the resulting smoke pattern. Some of these tests were conducted with a translucent polyethylene covering on the front wall of the shredder in place of the plywood panels. Most of the smoke remained in the vicinity of the mill area (shaft, discs and hammers) for a period of 1-3 min depending on shaft speed and ambient winds. Air convection and diffusion eventually caused diluted smoke to exit primarily through the discharge grating at the bottom of the shredder. Some diluted smoke also drifted out the shredder inlet hood, but at a lower velocity.

Induced air flow rates through the shredder were estimated by velocity probe measurements and from observations of smoke mixing and clearing times. The measurements are described in Appendix B. The velocity probe data indicated a highly nonuniform flow pattern with velocities on the order of a few ft/s everywhere except in the immediate vicinity of the hammer circle. With a shaft speed of 900 rpm and 48 hammers, a net air flow rate of 3300-4000 cfm (1.5 - 1.9 $m^3/s$) going out through the inlet hood was calculated from these measurements.

### PROPANE MIXING TESTS

Propane was used for both the gas mixing and explosion tests. Several reported shredder explosions[1,2] have been attributed to propane, which has a higher vapor pressure than most commonly available flammable liquids, so it can be expected to vaporize and mix with air more readily than other liquids. Furthermore, previous explosion test programs[6,7] have shown that propane-air explosions are particularly difficult to vent effectively. Thus, it is felt that propane mixing and explosion tests represent realistic worst-case conditions for generating conservative explosion protection guidelines.

In both the gas mixing tests and the explosion tests, a pre-weighed quantity of propane was rapidly injected into the hammermill portion of the shredder Three different injection locations, designated as locations I, I' and J in Figure 1, were utilized. The measured weight of propane (1-3 lb) was fed into vertical pipe sections and attached via solenoid valves to orifices I and/or J in the shredder end walls 41 in. (104 cm) above the shaft centerline, i.e., about 8 in. (20 cm) above the hammer circle. Injection at I' was achieved with a 36-in. (91 cm) horizontal extension from I so as to inject at the same height but closer to the mid-shaft center plane. In all but one of these tests, liquid phase propane was injected. Films of the injection process indicated that the liquid propane consisted of a fine mist which rapidly vaporized as it mixed with air.

Propane concentrations were measured with an Anarad AR-400 infrared gas analyzer with a calibrated range of 0-8% propane by volume, and a response time of 5-15 s, depending on sample location. Sample locations are designated as locations A,B,C,D,D', and E in Figure 1. Locations A,B,C, and E are on the shaft end wall, while D and D' are on the rear wall midway along the shaft. A,D, and D' are situated at the shaft elevation; E and C are at the upper and lower ends of the 36-in. (91 cm) diameter disc circle, respectively; and B is about 5 ft (1.5 m) above the shaft elevation.

Typical measured propane concentration histories at different locations are shown in Figures 4 and 5. The 2.2% propane lower flammable limit line is also drawn in these figures to illustrate that flammable concentrations are highly transient. The peak concentrations in these figures are highest for the location nearest the injection site, i.e., location E in Figure 4 and location A in Figure 5.

Peak concentration data for all the gas mixing tests are shown in Table 1. For concentrations exceeding the lower flammable limit, the durations of the flammable portion of the concentration histories are also listed in Table 1. For example, the peak concentration at location A in Test 7 (2 lb of propane, 660 rpm shaft speed) was 2.6% and the concentration exceeded the lower flammable limit for 6 s.

Peak concentrations at sample location A (at the end of the shaft) were consistently higher than at locations D and D' (midway along the shaft). This is illustrated in Figure 6 in which peak end shaft concentrations and mid shaft concentrations are plotted as a function of the amount of propane injected. The higher end shaft concentrations are probably due to the lower induced air velocity at the end of the shaft. Therefore, an air sweeping device installed at the end of the shaft, such as the weld beads used by Ahlberg and Boyko[3] for eliminating combustible debris accumulation near rotor end discs, may significantly reduce the chances of forming pockets of gas-air mixture in the explosive range. In the absence of such an air sweeping device, location A is a consistent potential ignition site, as was the case in the explosion tests in this project.

Perhaps the most striking feature of the data obtained for tests with the open discharge area (the first seven mixing tests) is that the peak concentrations were under the lower flammable limit at all locations except A

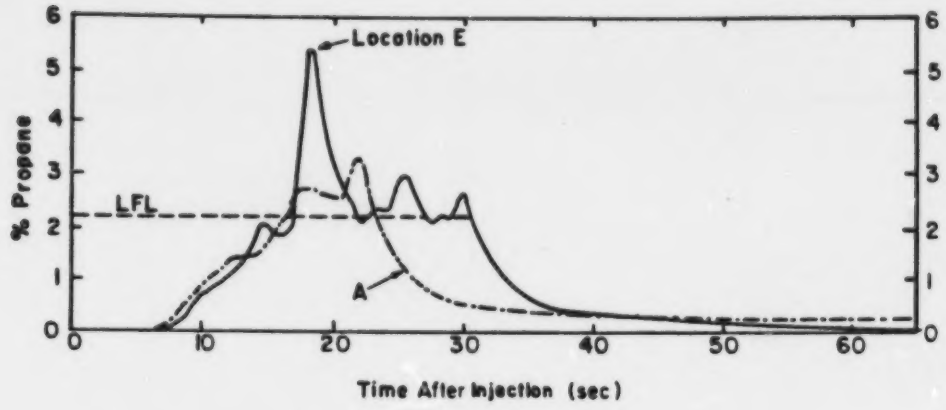


Figure 4. Propane concentration histories at two locations during gas mixing test 2.

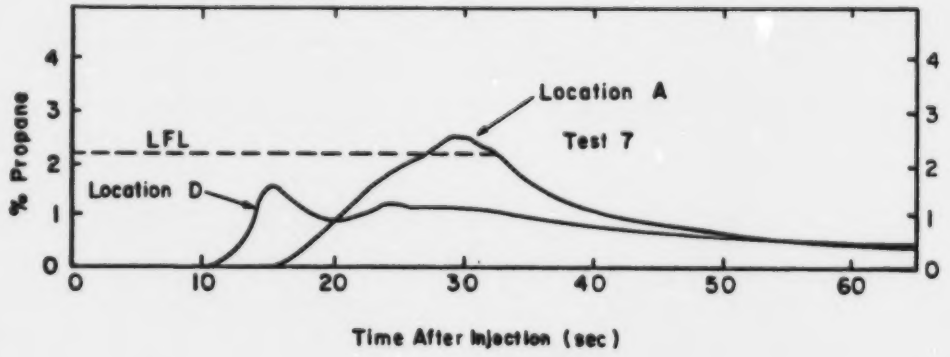


Figure 5. Propane concentration histories at two locations during gas mixing test 7.

Table 1. Gas Mixing Data

| Test # | Shaft Speed (rpm) | Injector Location | Total wt of Fuel (lb) | Sample Location A $C_{max}$* | A T+ | B $C_{max}$ | B T | C $C_{max}$ | C T | D $C_{max}$ | D T | D' $C_{max}$ | D' T | E $C_{max}$ | E T | Open or Closed Bottom |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 260 | I | 1 | >8 | 25 | 0.5 | - | 2.0 | - | 1.6 | - | - | - | - | - | Open |
| 2 | 680 | I | 1 | 3.25 | 10 | - | | - | | 0.8 | - | 0.9 | - | 5.5 | 10 | Open |
| 3 | 690 | I' | 1 | - | - | - | - | - | - | 1.5 | - | 1.1 | - | 0.5 | - | Open |
| 4 | 480 | I | 1 | 2.75 | - | - | - | - | - | 1.0 | - | 1.0 | - | - | - | Open |
| 5 | 690 | I,J | 2 | 4.0 | 18 | - | - | - | - | 1.0 | - | - | - | - | - | Open |
| 6 | 660 | I,J | 3 | 8.0 | 31 | - | - | - | - | - | - | - | - | - | - | Open |
| 7 | 660 | I,J | 2 | 2.6 | 6 | - | - | 0.5 | - | 1.6 | - | - | - | - | - | Open |
| 8 | 660 | I,J | 2 | 3.6 | 20 | - | - | - | - | - | - | - | - | - | - | Closed |
| 9 | 660 | I,J | 2 | 7.5 | 15 | - | - | - | - | - | - | - | - | - | - | Closed |
| 10 | 660 | I,J± | 2 | 1.6 | - | - | - | - | - | - | - | - | - | - | - | Closed |

* $C_{max}$ = maximum concentration (vol %).

+ T = flammable concentration.

± Propane gas injected in the gas phase (top injection) in the last test and in the liquid phase (bottom injection) in the first eight tests.

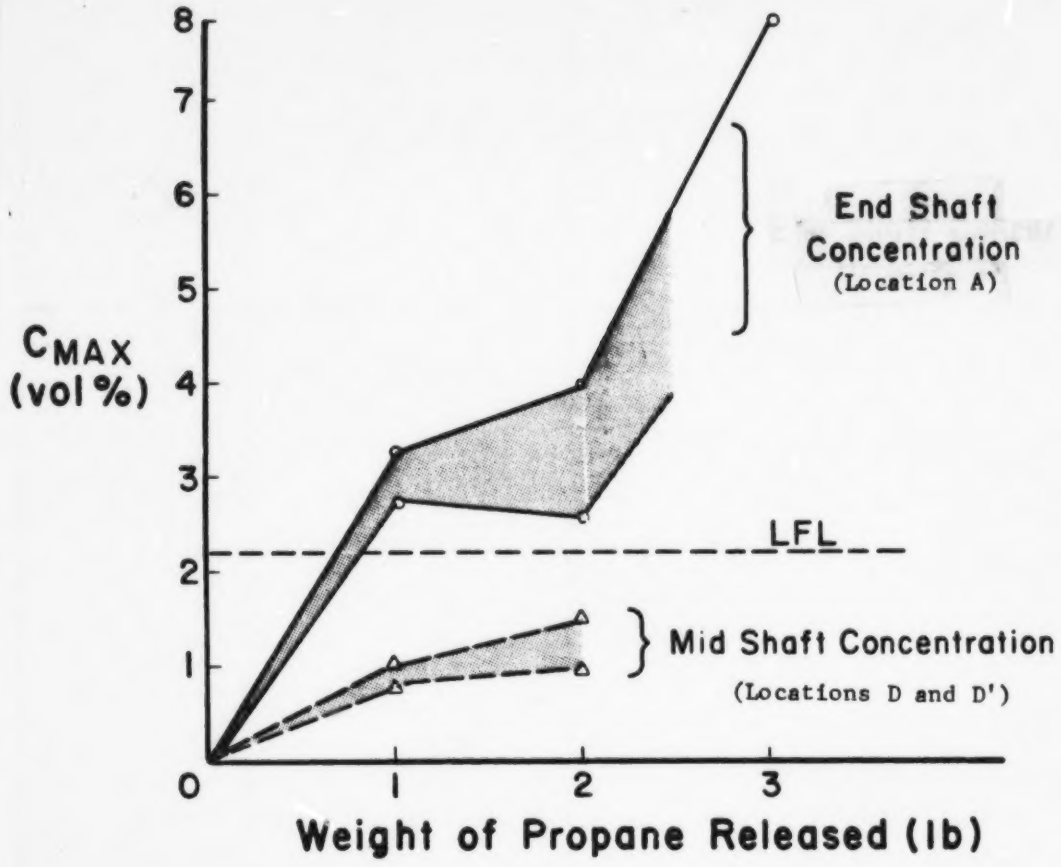


Figure 6. Peak propane concentration versus amount injected at end of shaft (unobstructed discharge - 660-rpm shaft speed)

(and E in one test). This implies that flammable mixtures created from the release of 2 lb (1 kg) or less of flammable vapor are confined to a very small portion of the hammermill near the end walls. Therefore, the chances of igniting a violent explosion are quite small unless much more than 2 lb of flammable vapor is released, or the shredder inlet and discharge areas are obstructed. This conclusion is consistent with reports[2,3] that shredder explosion damage usually results from either a large prolonged release of flammable vapor (for example, from a whole case of flammable solvent), or from gas accumulation in a jammed shredder.



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## SECTION 4

## EXPLOSION TEST PROCEDURE AND INSTRUMENTATION

Explosion tests in the shredder mock-up were conducted with propane-air mixtures of varying size and concentrations in the range 3.5-4% by volume. These concentrations are somewhat less than the propane concentration (5.2%) at which the highest pressures were measured in previous explosion venting test programs[5,6]. The strategy here was to eventually conduct tests at higher concentrations, but pressures at the lower concentrations were too high to proceed to "worst-case concentrations."

Gas mixtures for the first two tests were formed by rotor-induced mixing with open inlet and discharge areas. However, this unrestrained mixing resulted in a very weak explosion in the first test and in no explosion at all (after three attempts) in the second test. Therefore, subsequent tests were conducted by confining the gas mixture with polyethylene sheets.

An electric match was used for the ignition source in the first few tests; later tests were fired by a 12-Joule condenser spark discharge. The electric match in the first test was placed near location A in Figure 1 because the highest concentrations were measured there in the gas mixing tests. In subsequent tests with a more uniform gas mixture, the ignition source was at location D, which is closer to the center of the hammermill.

Explosion pressures have been measured with two Dynisco Model PT321 strain gage transducers* with a calibrated range of 0-10 psig (0-69 kPa). One transducer labeled Gage B, was mounted on one side wall of the shredder, 41 in. (104 cm) directly above the shaft (location PTB in Figure 1). The other transducer, called Gage A, was installed in the opposite side wall, 2 ft (0.61 m) below the top of the shredder (location PTA in Figure 1). Transducer output was wired to signal conditioning amplifiers and then in parallel to an oscillograph and a FM analog magnetic tape recorder. Data on the analog tape recorder was subsequently digitized and stored on a Hewlett-Packard 2114 minicomputer. Videotapes and high-speed movies have also been obtained for most of the explosion tests.

The 55-ft$^2$ (5.1 m$^2$) cross-sectional area at the top of the shredder was available for explosion venting in all the tests. In all but the last test, the four plywood panels atop the shredder were outfitted with collapsible washer fasteners such that the nominal panel release pressure was in the range 0.2-0.4 psig. In the first two tests, pressures did not reach these

*In the last test, Celesco Model P2805 pressure transducers (with a range of 0-15 psig) were utilized.

values, so the vent panels did not deploy. In subsequent tests, the panels did deploy but not until pressure reached 1.1-2.5 psig.

Various panel restraint techniques were employed. Some panels were hinged only, some were tethered by aircraft cable, and others were both hinged and cabled. In the more violent explosions, none of these restraining methods were completely successful. A similar lack of success with blow-off panel tethers (for building panels) has been reported in the accounts of the Ontario shredder explosions[3]. One promising technique which has recently been tested successfully in another project[8] is the use of a jerry-rigged shock-absorbing arrangement for the cables.

In the last test, the four plywood panels atop the shredder were replaced with 4 mil (0.10 mm) thick polyethylene film designed for a nominal tear pressure of 0.3 psig. The polyethylene film eliminated vent panel inertia and tethering problems experienced in the earlier tests.

## SECTION 5

## EXPLOSION TEST RESULTS

Test conditions and peak pressure data are summarized in Table 2. A total of seven tests were run, not including the misfire in Test 2*. Peak pressures ranged from a low of 0.15 psig in Test 1 to a high of 15.4 psig in the last test.

Pressure-versus-time traces for Tests 3 through 8 are shown in Figures 7-12. Some of the traces have single peaks, e.g., Test 4, while others have multiple peaks, e.g., Test 6. Multiple peak pressure traces are often observed[6,7] in explosion venting tests involving self-induced flame accelerations, while single-peak traces are associated with highly turbulent combustion (due here to relatively high shaft speeds).

It is evident from the data in Table 2 that peak pressures were significantly affected by mixture volume, shaft speed, and vent deployment pressure. Of these independent parameters, the variation with shaft speed is particularly dramatic, as illustrated in Figure 13. The apparent nonlinear variation with shaft speed depicted in Figure 13 may have been due in part to the increased turbulence caused by the additional hammers used in the 900-rpm test (Test 8). Peak pressure variation with the quantity $n\Omega$ (number of hammers x shaft speed), as shown in Figure 14, is almost linear†. The nondimensional parameter $nr\Omega/S_\ell$, where $r\Omega$ is hammer tip speed and $S_\ell$ is the laminar burning velocity of a stoichiometric propane-air mixture (1.5 ft/s), is also shown as the abscissa in Figure 14.

Peak pressures measured by Gage A at the top of the shredder were consistently higher than the peak pressures measured by Gage B in the hammermill portion of the shredder. This is probably due to precompression of unburned gas ahead of the propagating flame which was ignited in the hammermill and then traveled up and out the top of the shredder. This flame propagation was apparent in the videotapes which showed flame venting out of the bottom discharge of the shredder well before (60-200 msec) flame was vented through the vent on top of the shredder.

---

*The Test 2 misfire was probably caused by too long a time delay between propane injection and ignition. This problem was eliminated in subsequent tests by confining the propane-air mixture with polyethylene film across the inlet and discharge openings on the shredder

†Although the apparent linear relationship with $n\Omega$ may be aesthetically appealing, the nonlinear variation with $\Omega$ is predictable on the theoretical grounds described in Section 6 - Comparison With FMRC Computer Model.



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Table 2. Shredder Explosion Test Data

| Test No. | Propane Concentration (%) | Mixture Volume ($ft^3$) | Mixture Volume (% of Shredder)* | Shaft Speed (RPM) | Vent Area+ ($ft^2$) | Vent Release Pressure (psig) Static | Vent Release Pressure (psig) Actual | $P_{max}$ (psig)± Gage A (Top) | $P_{max}$ (psig)± Gage B Mill) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.4 | Uncontrolled Mixing | | 690 | 0 | 0.4 | - | 0.15 | - |
| 3§ | 3.5-4.0 | 700 | (44) | 690 | 55 | 0.4 | 2.5 | 2.7 | 2.6 |
| 4 | 4.0 | 700 | (44) | 438 | 55 | 0.3 | 1.1 | 1.3 | 1.1 |
| 5 | 3.8 | 700 | (44) | 660 | 55 | 0.3 | # | 2.0 | 1.7 |
| 6 | 3.6 | 1600 | (100) | 250 | 55 | 0.2 | 1.3 | 4.8 | 3.1 |
| 7 | 3.7 | 1600 | (100) | 660 | 55 | 0.2 | 1.75 | - | 4.3 |
| 8 | 3.9 | 1600 | (100) | 900** | 55 | 0.3 | 1.7 | 15.4 | 9.5 |

* Percentages of shredder volume are based on volume excluding inlet hood.

\+ Vent area does not include shredder discharge area or inlet hood area.

± 1 psig = 6.4. kPa.

§ Test 2 did not produce an explosion because the uncontrolled mixing resulted in the ignitor firing a few seconds too late.

\# The actual vent release pressure is not known for Test 5 because the oscillograph was started too late.

** 48 simulated hammers were installed on the shaft in Test 8, while only 16 hammers were used in Tests 1-7.

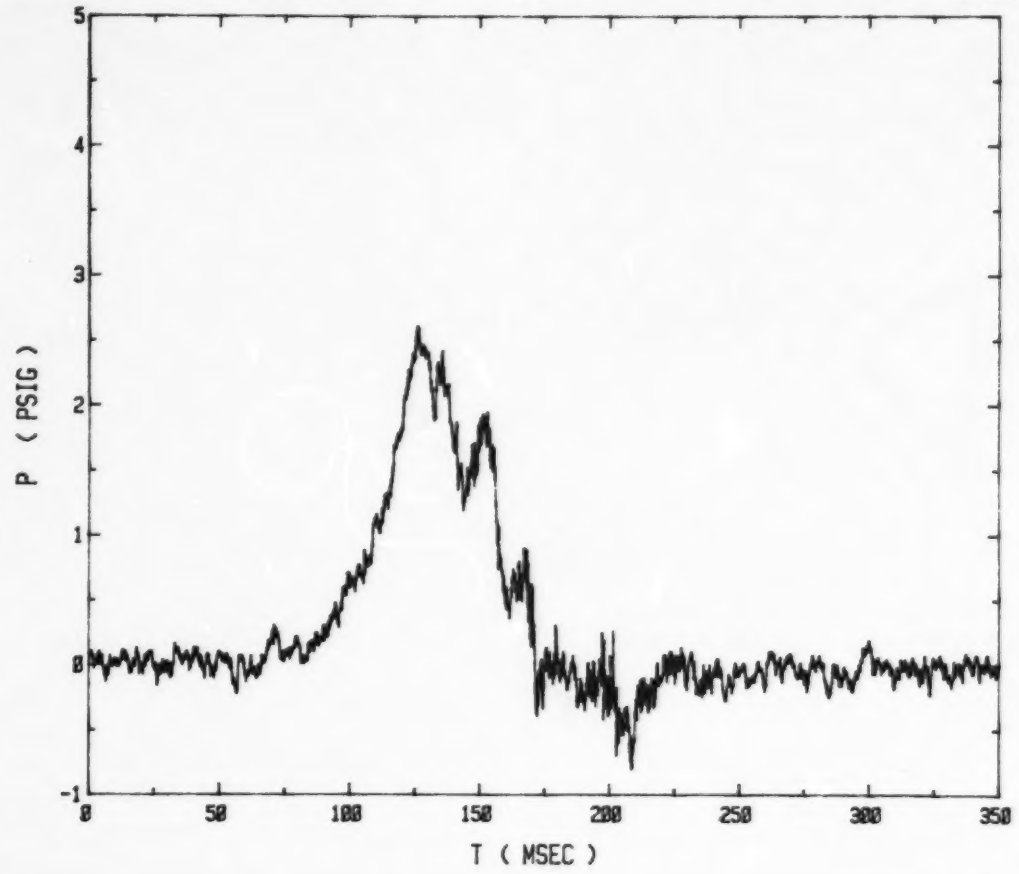


Figure 7. Shredder explosion Test 3 - Gage A

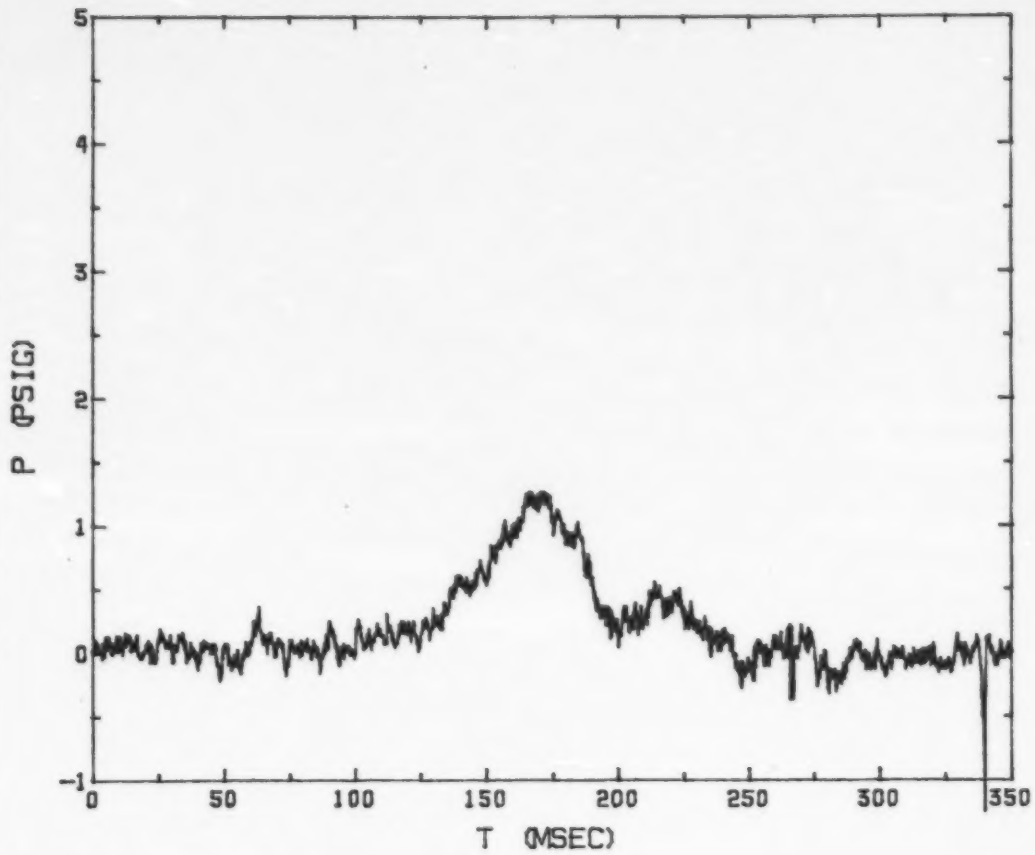


Figure 8. Shredder explosion Test 4 - Gage A

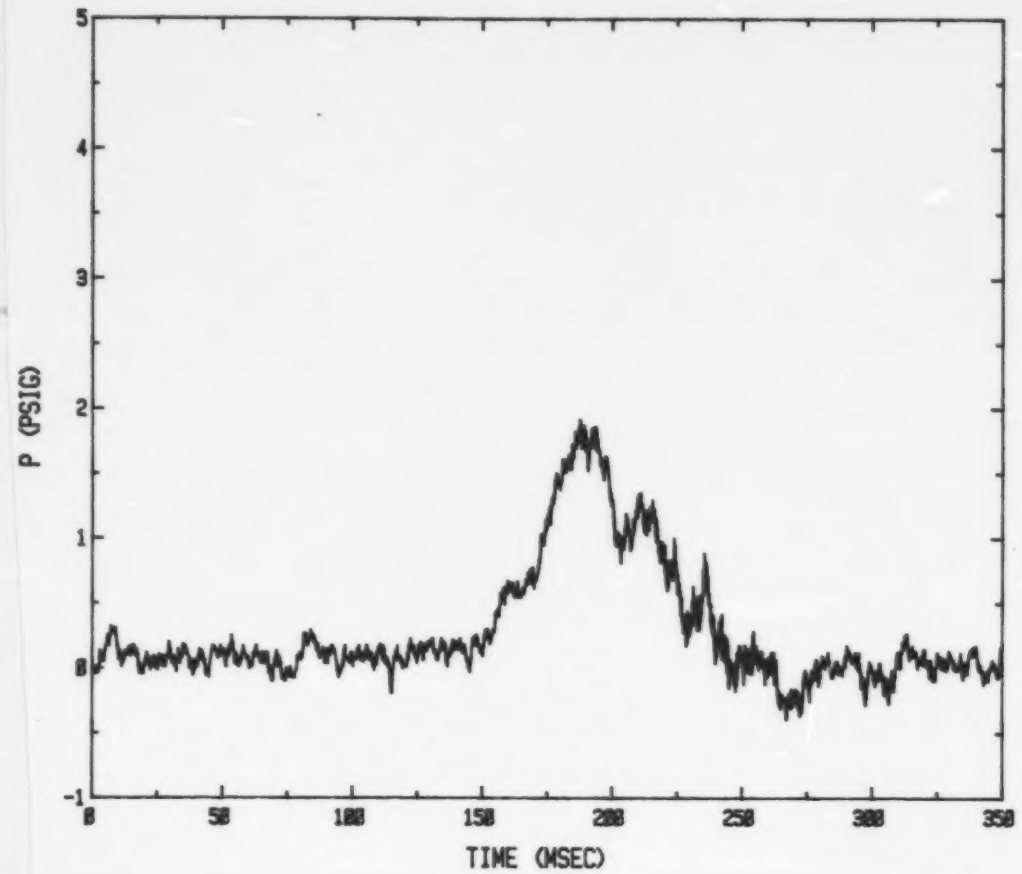


Figure 9. Shredder explosion Test 5 - Gage A

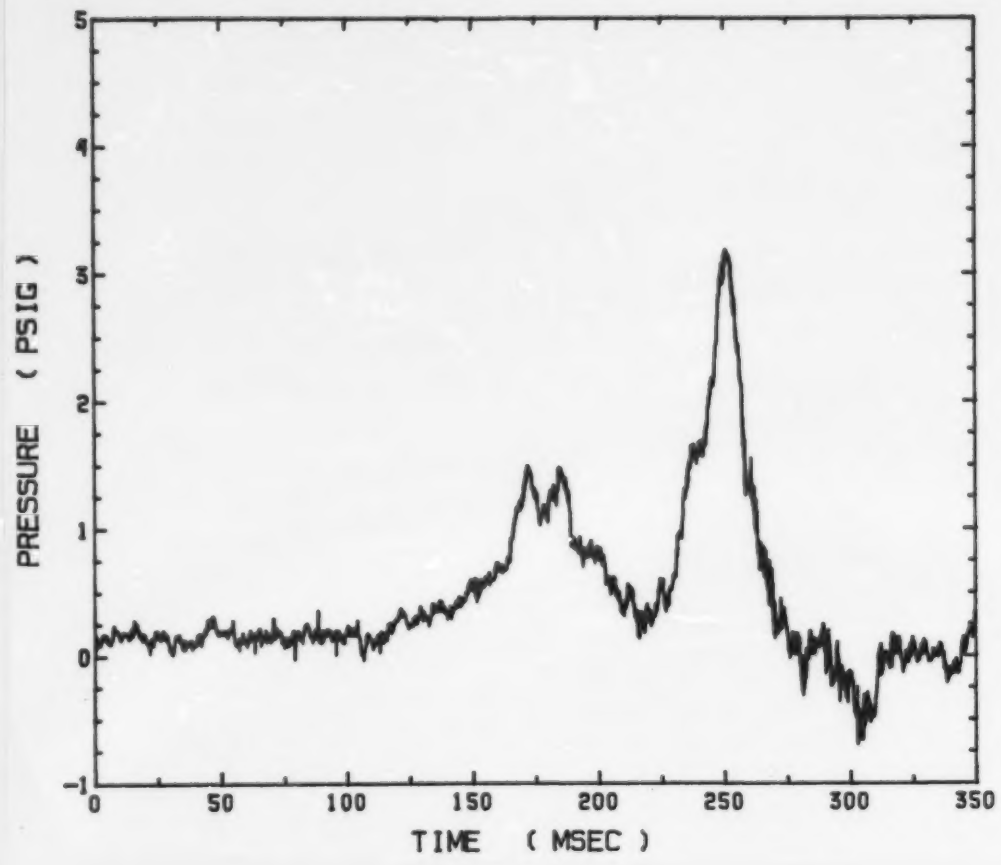


Figure 10. Shredder explosion Test 6 - Gage B

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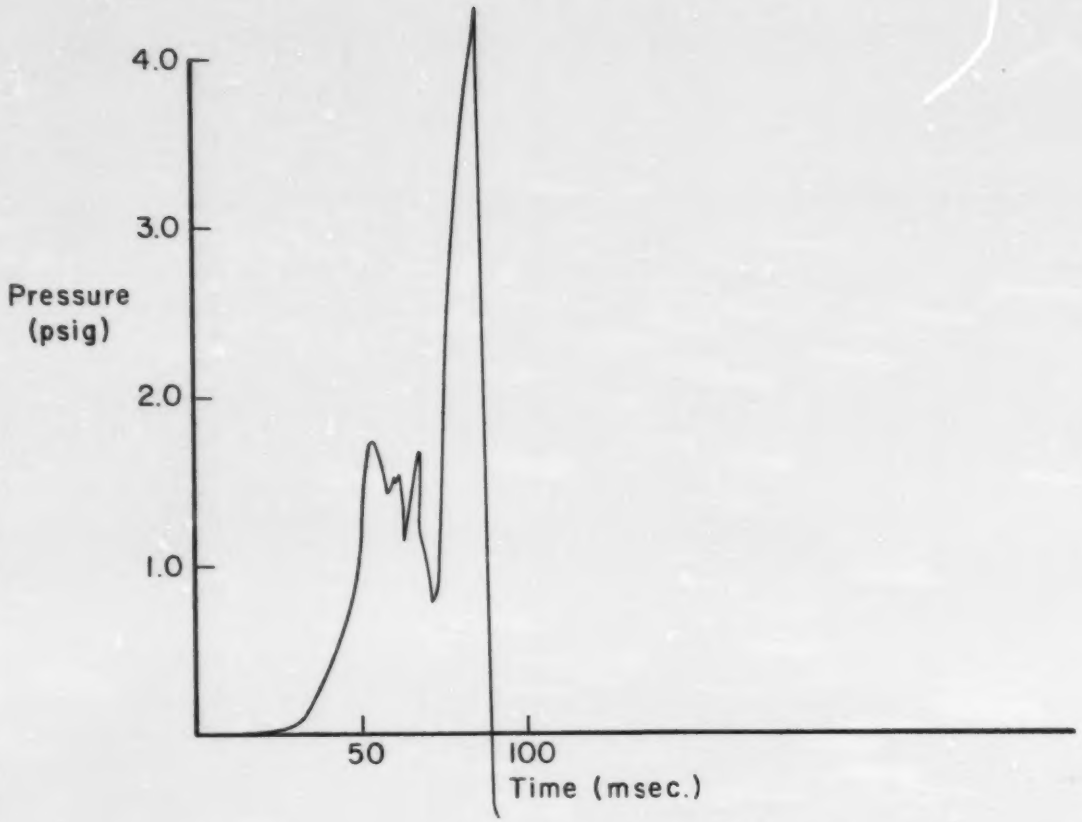


**Figure 11. Pressure trace for Gage B in Explosion Test 7**

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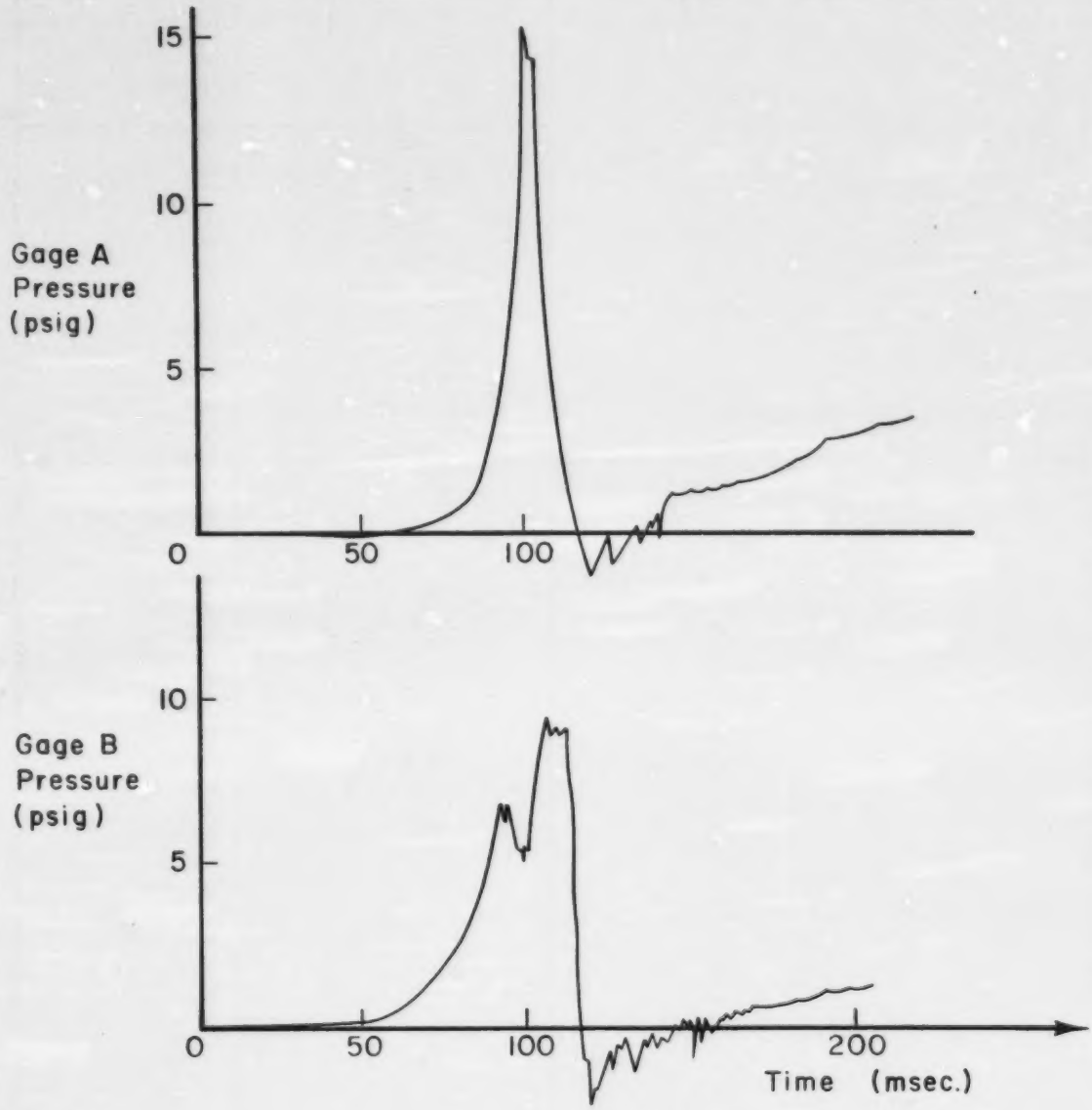


**Figure 12. Pressure traces on Gage A (top) and Gage B (bottom) during Explosion Test 8**

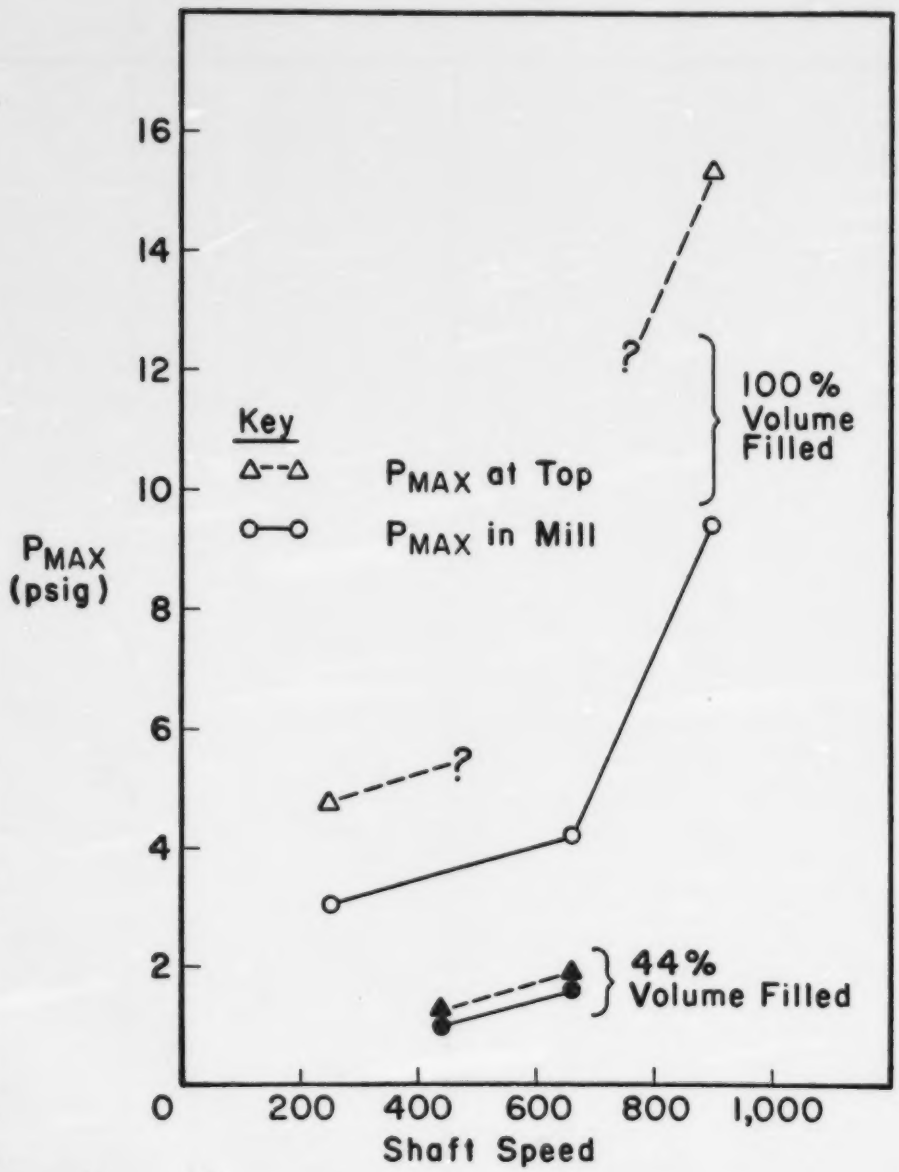


**Figure 13** Peak pressure versus hammermill shaft speed

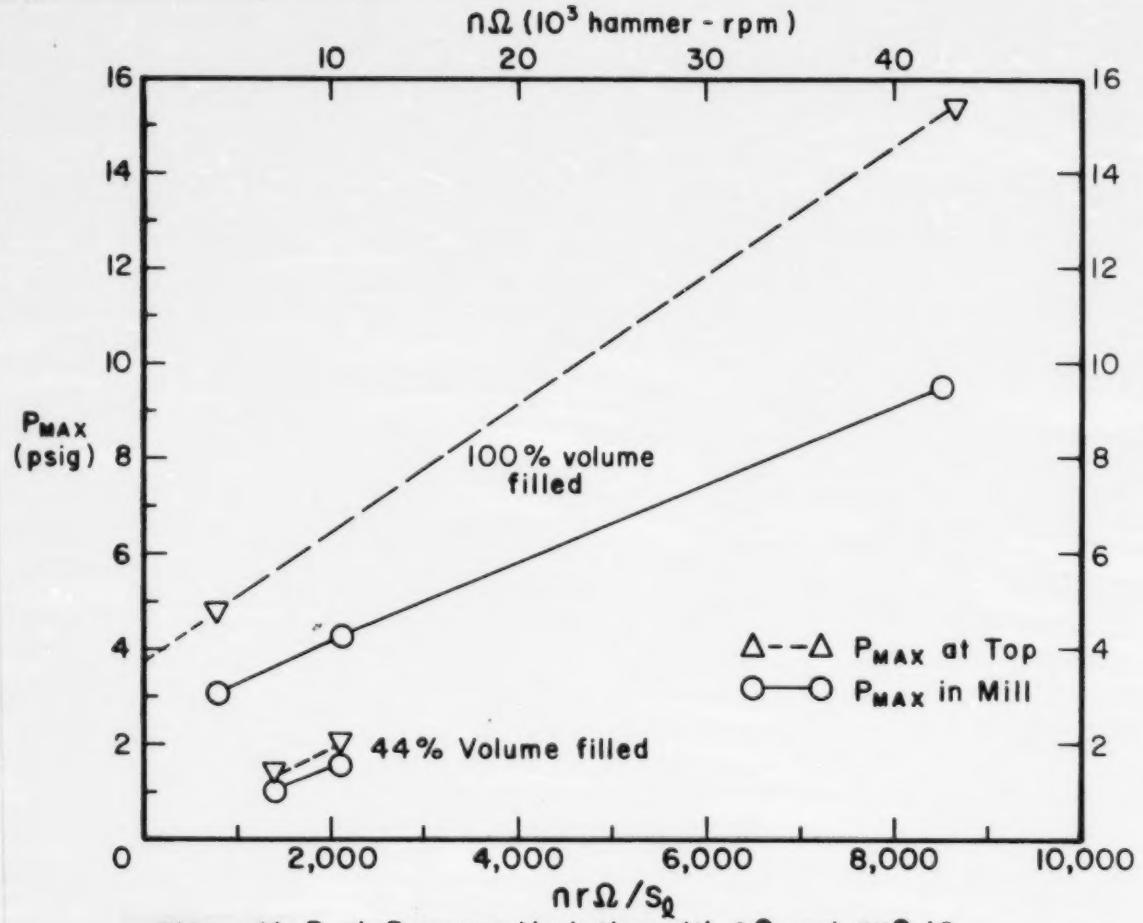


Figure 14. Peak Pressure Variation with $n\Omega$ and $nr\Omega/S_\ell$

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The test sequence indicated in Table 2 involved generally increasing explosion severity. The last test (Test 8) was considerably more violent than the preceding tests, and the unexpectedly high peak pressure produced significant damage to the test structure. There were weld failures and deformed members of the steel frame, as well as bolt fastener failures allowing the plywood panels to blow off the structure. This damage was primarily confined to the top half of the shredder, which experienced a significantly higher pressure (15.4 psig) than the hammermill section (9.5 psig).

Many operating shredders would also experience significant damage at the high pressure loads experienced in Test 8. In fact, some of the more violent reported MSW shredder explosions have also involved severe damage to the shredder feed hood (directly above the hammermill), similar to that incurred at the top of the mock shredder frame during Test 8. Thus, the convenient explosion venting configuration utilized for the mock shredder tests, and recently installed in several MSW processing plants, will not prevent serious damage during worst-case gas explosions unless the shredder is strengthened to withstand pressures of about 15 psig.

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## SECTION 6

## DATA COMPARISON WITH EXPLOSION VENT DESIGN GUIDELINES

There have been several ambiguities in recent attempts to apply existing explosion venting design guidelines to MSW shredders. These include 1) the inclusion of the extreme shredder turbulence level in the design guidelines; 2) the effective venting capacity of the shredder inlet and discharge areas; 3) the multitude of published guidelines which often recommend widely different vent areas for a given allowable overpressure. In order to resolve some of these ambiguities, peak pressures in the last three explosion tests (in which the shredder was completely filled with a flammable gas mixture) have been compared to the pressures expected on the basis of some contemporary explosion venting guidelines and data correlations.

### COMPARISON WITH NFPA 68 GUIDELINES

The most recent (1978) version of the NFPA Guide for Explosion Venting[4] recommends use of the Runes equation for determining required vent areas for explosions inside buildings and use of the Bartknecht nomographs for explosions inside equipment. Peak pressures expected on the basis of both these guidelines are indicated on the bar graph in Figure 15. Two results are indicated for the Bartknecht nomographs because NFPA 68 (pp 68-81) suggests that turbulent propane explosions may be considered tantamount to quiescent hydrogen explosions (with a corresponding increase in burning velocity) for the purpose of estimating required vent areas*. In each case, the peak pressure has been estimated first for a vent area of 55 $ft^2$ (5.1 $m^2$), corresponding to the available vent area at the top of the shredder. The resulting estimated peak pressures are: 5.1 psig for the Bartknecht propane nomograph, 7.6 psig for the Runes equation (for propane), and 8.8 psig for the Bartknecht hydrogen nomograph. When these values are compared to the pressures developed during Tests 6 and 7, i.e., 4.3-6 psig, it is clear that the Bartknecht propane nomograph agrees quite well with the measured data for relatively moderate turbulence levels.

Expected pressures have also been estimated on the basis of the sum of the top vent area plus the 30 $ft^2$ (2.8 $m^2$) bottom discharge area. The resulting estimated pressures, which are indicated by the shaded bars in Figure 15, are 3 psig or less. Since the actual measured pressures were higher than 3

*Contrary to the suggestion in NFPA 68, Bartknecht's recent textbook (Reference 9, p 112) states that his quiescent mixture nomograms are also applicable to turbulent initial conditions providing peak expected pressures are less than about 1 bar (14.5 psig) and the ignition source is the same for the quiescent and turbulent mixtures.

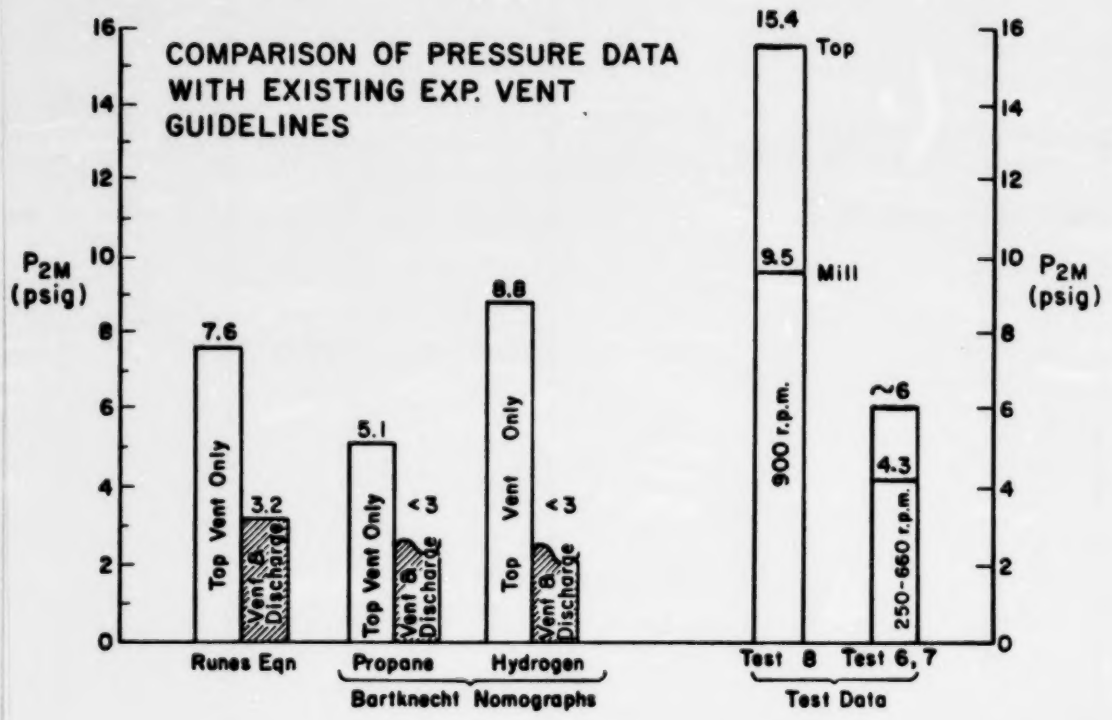


**Figure 15** Comparison of pressure data with existing explosion vent guidelines

psig, the difference can be attributed to the fact that the discharge area (which is only 3 ft (1 m) above the ground) is not a very effective vent relief area.

As Figure 15 illustrates, the measured peak pressures in Test 8 are much higher than expected on the basis of any of the guidelines, even when the effective vent area is assumed to be only the unobstructed top vent area. Thus, none of the NFPA 68 guidelines adequately account for the dramatically higher pressures generated at a shaft speed of 900 rpm with 48 hammers. This is particularly true for the pressure at the top of the elongated shredder (Height/Width ratio = 4) where precompression of unburned gas can aggravate the turbulent combustion problem. New or modified guidelines are needed in which the relationship between peak pressure and turbulence level is quantified in terms of shredder operating parameters and for the shredder geometry. Section 6-Comparison With FMRC Computer Model presents such a modified guideline by incorporating a data correlation for Tests 6-8 into a previously developed mathematical model for vented gas explosions.

## COMPARISON WITH FMRC COMPUTER MODEL

The FMRC mathematical model to calculate transient overpressures during vented gas explosions was originally developed and documented by Yao et al[10]. Yao has shown[11] that calculated overpressures agree with experimental data providing the empirical value of the turbulent burning velocity parameter, $\chi$, is prescribed correctly. Calculations have recently been run for propane-air explosions with various values of $\chi$ and with varying vent areas and enclosure volumes. Computed results satisfy the following curve-fit equation:

$$P_{2M} = 0.0029 \left(\frac{\chi V^{2/3}}{C_v A_v}\right)^{2.3} \qquad (1)$$

for $0.025 \leq \frac{\chi V^{2/3}}{C_v A_v} \leq 0.08$; i.e., 1 psig $\leq P_{2M} \leq$ 15 psig;

and

$P_{2M}$ = peak pressure (psig) associated with vent area for vent release pressures small compared to $P_{2M}$;
$V$ = enclosure volume ($ft^3$);
$A_v$ = net vent area ($ft^2$);
$C_v$ = vent flow discharge coefficient (usually = 0.60);
$\chi$ = ratio of turbulent to laminar burning velocity.

Our objective here is to derive an appropriate equation for $\chi$ in terms of shredder shaft speed and possibly hammer characteristics. A wide assortment of equations relating $\chi$ to general turbulence parameters have been hypothesized in the combustion literature. Of the various published equations for $\chi$ reviewed by Andrews et al[12], the Kozachenko equation is the most appealing on the basis of both physical intuition and easy adaptation to shredder parameters. The Kozachenko equation is[13]:

$$\chi = 1 + u'/u_\ell + u''/u_\ell \qquad . \qquad (2)$$

where

$u'$ = root mean square turbulent velocity fluctuation prior to combustion;
$u''$ = turbulent velocity generated by flame;
$u_\ell$ = laminar burning velocity.

For a hammermill, it is logical to relate $u'$ to hammer speed, $V_H$. Thus,

$$u' = \eta v_H = \eta \Omega D/2 \quad , \tag{3}$$

where

$\eta$ = turbulence intensity coefficient in hammermill;
$\Omega$ = shaft speed; and
$D$ = hammer circle diameter.

Equations (2) and (3) can be combined in the form:

$$\chi = a_o + a_1 \Omega \tag{4}$$

where

$a_o = 1 + u''/u_\ell$;
$a_1 = u'/(\Omega u_\ell) = \eta D\pi/(60\gamma u_\ell)$.

Appropriate values for $a_o$ and $a_1$ can be estimated, either from theoretical approximations or from curve fits to the shredder explosion data. For example, a theoretical value of $a_o$ can be estimated by the Kozachenko-Karlovitz equation for wrinkled flame-generated turbulence. For an unburned gas to burned gas density ratio of 8 (for a stoichiometric propane-air mixture) and $u'/u_\ell \gg 1$, eq (6) of Reference 13 suggests $u''/u_\ell \simeq 4$, so that $a_o \simeq 5$.

Similarly, the value of $a_1$ can be obtained from estimated values of the turbulent intensity coefficient, $\eta$, in the hammermill. In lieu of any turbulent velocity measurements in the hammermill itself, we can resort to a typical value of $\eta$ used by Andrews et al[12] for a variety of turbulent combustion configurations. Thus, if we set $\eta = 0.05$ (and $D = 5$ ft and $u_\ell = 1.5$ ft/sec), we obtain: $a_1 = 0.0089\ (\text{rpm})^{-1}$.

Substitution of eq (4) into eq (1), and assuming $C_v = 0.60$, yields the following equation for peak pressure:

$$P_{2M} = 9.4 \times 10^{-3} \left(\frac{V^{2/3}}{A_v}\right)^{2.3} (a_o + a_1 \Omega)^{2.3} \quad . \tag{5}$$

Once the effective vent ratio, $V^{2/3}/A_v$ is specified, eq (5) can be used to correlate the shredder explosion data. As in the preceding sections, the shredder volume will be set equal to 1540 ft$^3$ (43.6 m$^3$), which is the volume excluding the feed hood, i.e., the volume occupied by flammable mixture in Tests 6-8. The effective vent area is equal to the top vent area plus some fraction of the discharge area. If we assume, for simplicity, that this fraction is one half, then $A_v = 55 + 15 = 70$ ft$^2$ (6.5 m$^2$) and $V^{2/3}A_v = 1.9$.

Insertion of $V^{2/3}/A_v = 1.9$ into eq (5) gives

$$P_{2M} = 0.041\ (a_o + a_1\Omega)^{2.3} \quad . \tag{6}$$

Equation (6) has been evaluated with the preceding theoretical values of $a_o$ and $a_1$ to obtain the solid curve plotted in Figure 16. The calculated pressure obtained with these coefficients is midway between the two peak pressures measured in Test 6 and within 4% of the highest pressure in Test 8.

The other approach to finding appropriate values for $a_o$ and $a_1$ is to set the calculated $P_{2M}$ exactly equal to the data in Tests 6 and 8. If we use the highest pressures (measured at the top of the shredder) in these tests, we obtain $a_o = 5.9$ and $a_1 = 0.0081\ (rpm)^{-1}$. If we use the average of the two measured peak pressures, we obtain $a_o = 5.5$ and $a_1 = 0.0073\ (rpm)^{-1}$. The resulting curves as a function of shaft speed are also shown in Figure 16.

Although all three sets of coefficients do not differ by much, the author recommends use of the theoretical values for estimating peak pressures for different shredder configurations. The recommended equation, written in terms of hammer velocity, $v_H$, is

$$P_{max} = 9.4 \times 10^{-3} \left(\frac{V^{2/3}}{A_v}\right)^{2.3} (5 + 0.034\ v_H)^{2.3} \tag{7}$$

where $v_H$ is expressed in ft/sec; and $P_{max}$, in psig. Equation (7) is included in the proposed shredder explosion venting guidelines (Appendix A).

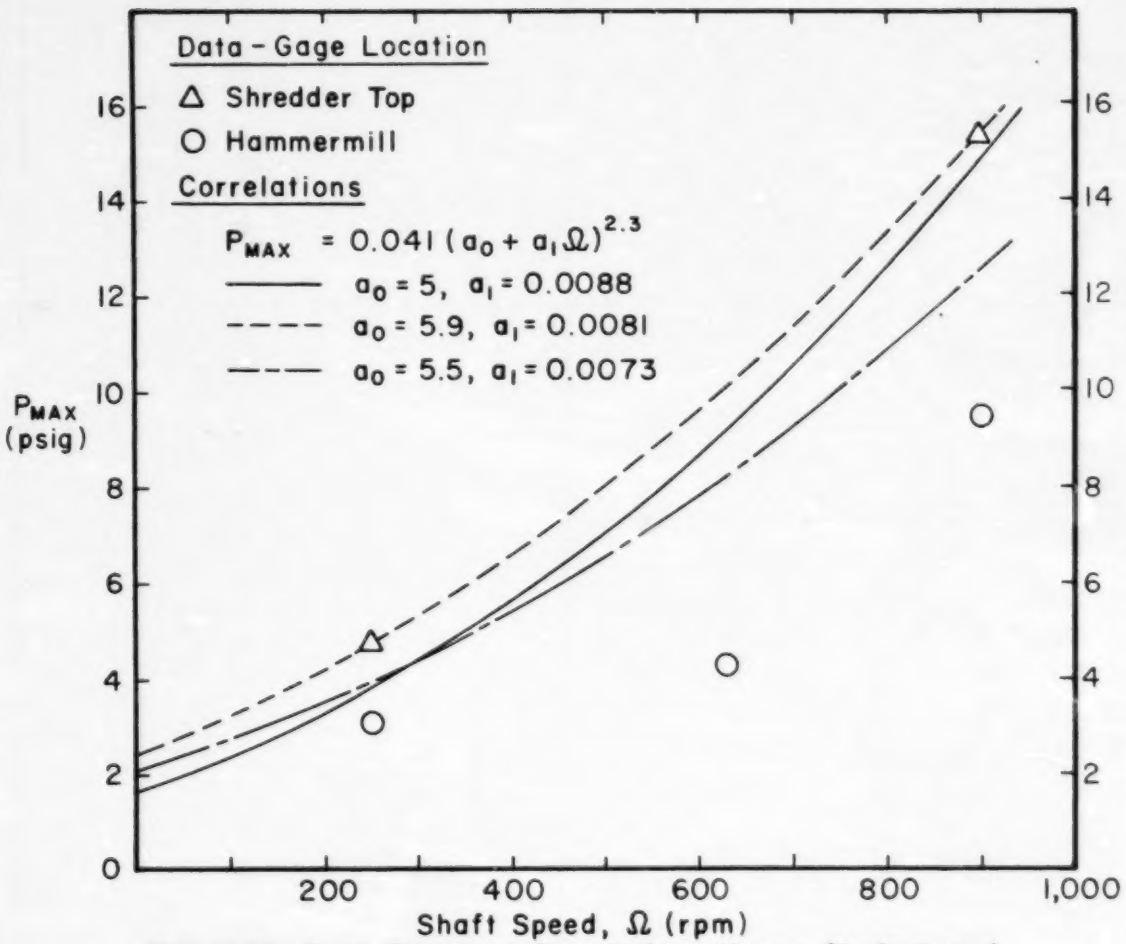


Figure 16. Peak Pressure Correlations Versus Shaft Speed

## SECTION 7

## CONCLUSIONS

Test results clearly lead to the following conclusions:

1. The probability and severity of an MSW shredder explosion are highly dependent upon the amount of flammable gas released, the presence of obstructions in the inlet and discharge area, and the hammermill shaft speed and number of hammers. Flammable vapor releases of approximately 2 lb (1 kg) or less in a large unobstructed shredder (with a volume on the order of 1500 $ft^3$) are unlikely to produce damage, even in the absence of explosion venting. Larger releases or obstructed inlet and discharge areas require special explosion protection measures because they can lead to relatively large flammable mixtures in the shredder.

2. Explosion venting effectiveness is quite sensitive to shredder turbulence level as determined by shaft speed and number of hammers. Venting through the entire top of the shredder should effectively maintain pressures, for near-stoichiometric gas mixture explosions, under 6 psig if the shaft speed is less than 700 rpm and there are 16 hammers or less. However, the same vent configuration will result in explosion pressures of 10-15 psig at a shaft speed of 900 rpm with 48 hammers.

3. If existing explosion vent design guidelines are utilized, little or no credit should be taken for venting through shredder inlet and discharge areas. The design guidelines in NFPA 68 (1978) provide reasonable estimates of peak explosion pressures at moderate shredder turbulence levels, but severely underestimate peak pressures at the high turbulence levels produced by 48 hammers rotating at 900 rpm.

4. A previously developed computer model of vented gas explosions has been used to compare calculated peak pressures to data in the most severe tests. Calculated and measured data agree well when the ratio, $\chi$, of turbulent to laminar burning velocity ($u_\ell$), is given by $\chi = 5 + 0.05\ v_H/u_\ell$, where $v_H$ is hammer tip velocity in the shredder.

5. A suggested guideline for shredder explosion venting has been prepared (Appendix A) on the basis of test results, analysis, and a review of other published explosion venting design criteria.

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# APPENDIX A

## GUIDELINES FOR SHREDDER EXPLOSION VENTING

### PREFACE

The following guidelines are submitted as an Appendix to this report in partial fulfillment of the requirements of EPA Contract No. 68-03-2880. The guidelines are based, in part, on test data described in the main body of the report, and partly on contemporary explosion venting technology as described in the references. Factory Mutual has also submitted this Appendix to ASTM Subcommittee E-38.07 (Health and Safety Aspects of Resource Recovery) for review and possible inclusion in the ASTM Guidelines for Shredder Explosion Protection.

### INTRODUCTION

Explosion venting is a technique for limiting structural damage incurred during combustion explosions. This is achieved by allowing unburned gas and combustion products to be discharged from the shredder before the combustion reaction and accompanying maximum pressure rise is completed. Shredder explosion venting can provide effective protection during deflagration-type explosions involving most flammable gases and vapors, but it is not effective for detonations,* which might be caused by commercial explosives, military ordnance, and other easily detonable materials.

In general, low vented explosion pressures are achieved with large vent areas, low vent deployment pressures, low vent panel inertia (weight) and vent locations near the expected ignition site (which is usually the hammermill). The following quantitative guidelines for these factors are intended to protect against near worst-case flammable gas-air mixtures occupying the entire shredder internal volume. If the gas or vapor concentration is near the lower or upper flammable limit, or if the flammable mixture is confined to only a small fraction of the shredder volume, these criteria can be relaxed considerably. For example, explosions involving two pounds or less of hydrocarbon vapor in a large shredder (1500 $ft^3$ or more), do not require any special venting besides the usual feed and discharge openings.

### VENT AREA

Explosion vent areas should be sufficiently large to maintain explosion pressures under the damage threshold value for the particular shredder installation. Previously published guidelines relating peak pressure to vent area

*Detonations are explosions with supersonic flame (or other reaction front) propagation rates, whereas deflagrations involve subsonic flame propagation.

are not directly applicable to MSW shredders because shredder hammer velocities can increase the combustion rate well above that considered in establishing previous guidelines. The following recommended relationship is based on propane-air explosion tests conducted in a full-scale large shredder mock-up, including rotating hammers.

The vent area, $A_v$, required to maintain explosion pressures under the shredder damage threshold, $P_M$, is given by

$$A_v = 0.13\ V^{2/3} P_M^{-0.435}\ (5 + 0.034\ v_H) \qquad \text{(A-1)}$$

where V is the shredder internal volume, $v_H$ is the hammer velocity in ft/s, and $P_M$ is in units of psig. The calculated vent area will be in the same units as $V^{2/3}$.

If the shredder discharge grating is at least 3 ft above the discharge conveyor, half the discharge area can be credited toward attaining the required vent area, $A_v$. The difference should be made up with unobstructed explosion vents. No credit should be taken for the inlet area which is usually too obstructed and too far from the expected ignition site to be an effective vent.

To illustrate the use of eq (A-1), consider a hypothetical shredder with an internal volume of 1,000 $ft^3$, including the portion of the inlet hood directly above the hammermill. Let us suppose that structural calculations indicate that the weakest structural member can withstand an applied load equivalent to a hydrostatic pressure of 10 psig. At the design shaft speed in this shredder, the hammer tip speed is 250 ft/s. Substitution of these values into eq (A-1), results in a calculated required vent area of 64 $ft^2$. If the shredder discharge area is 20 $ft^2$, an explosion vent of at least 54 $ft^2$ area should be installed on the shredder.

VENT DUCTING

The explosion vent opening should discharge combustion gases and flame into an unoccupied outdoor area. If the shredder is situated inside a building vent ducting will be needed to channel gases and flame out of the building. This ducting should be kept as short as possible in order to avoid further burning and gas compression during venting.

There have been a few tests[A1-3] to determine vented explosion pressure variation with duct length. Data from a series of propane explosion tests with one specific vent ratio ($A_v/V^{2/3} = 0.10$) are shown in Figure A-1. Peak pressures increased continuously with duct length for duct length/diameter ratios of 0-20. At L/D = 20, peak pressures were 2-3 times as high as the pressures without any vent duct. In lieu of data for other vent ratios, it is suggested that Figure A-1 be utilized, but with peak pressures for zero duct length determined by eq (A-1). This will have to be done in an iterative procedure to insure that peak pressures with the vent duct do not exceed the damage threshold, $P_M$.

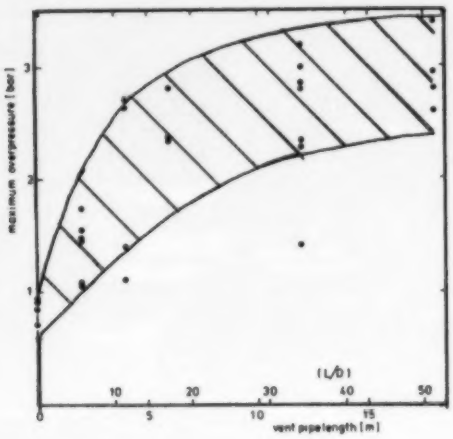



**Figure A-1** Explosion pressures of stoichiometric propane-air mixtures (propane concentration between 3.9 and 4.5%) in the 1 $m^3$ explosion vessel as a function of the tube length after the rupture membrane (polyester film 0.050 mm thick, static bursting pressure 0.29 bar, dynamic bursting pressure with the tested propane mixtures between 0.28 and 0.47 bar, F/V ratio 0.1 $m^{-1}$).
( from Ref. A-1 )

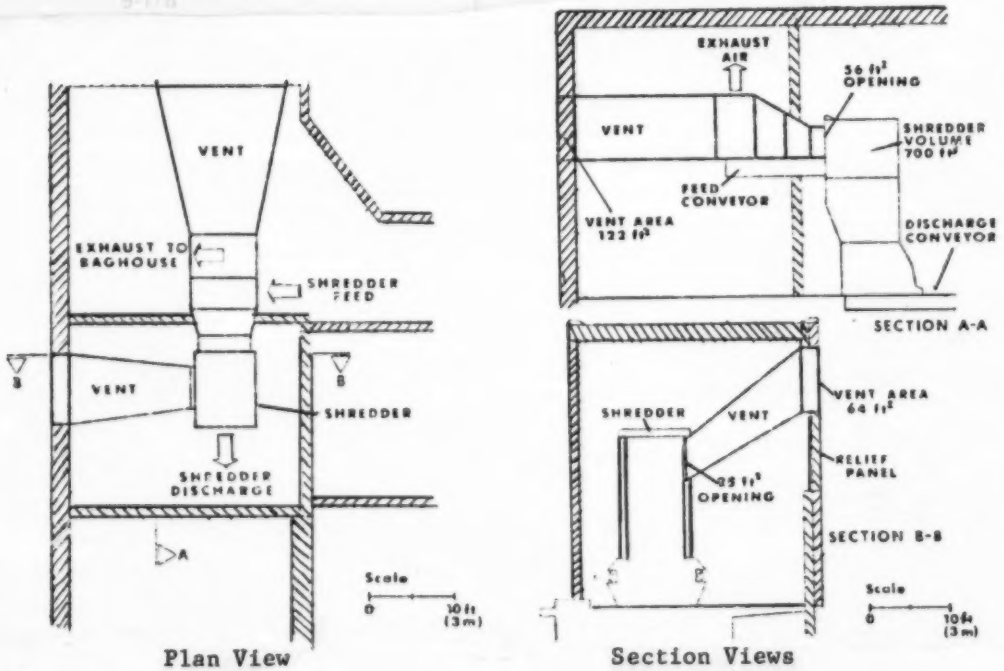



Fig. A-2 Vent Ducting Arrangement at Ontario Centre for Resource Recovery (from reference A-4)

If the pressure increases shown in Figure A-1, are intolerable, a duct with a diverging cross-sectional area should be utilized. Apparently, there has not been any published test data on how much divergence is required to prevent significant pressure increases above the unrestricted vent values given by eq (A-1). Figure A-2 is a drawing of a shredder installation in which diverging vent ducts have a more than 2 to 1 increase in cross-sectional area going from the shredder to the outer building walls. Even with large divergence angles as shown in Figure A-2, the vent duct should be designed to withstand a pressure equal to the shredder damage threshold pressure. Uniform cross-section ducts can be subjected to higher explosion pressures than those in the shredder, so they should be strengthened accordingly.

It is desirable to prevent flammable gas from entering a vent duct during normal shredder operation. This can be achieved by separating the vent duct from the shredder with a frangible explosion vent (either circular or rectangular) of the type made by rupture disc manufacturers. Several important aspects of vent cover design are described in the following section.

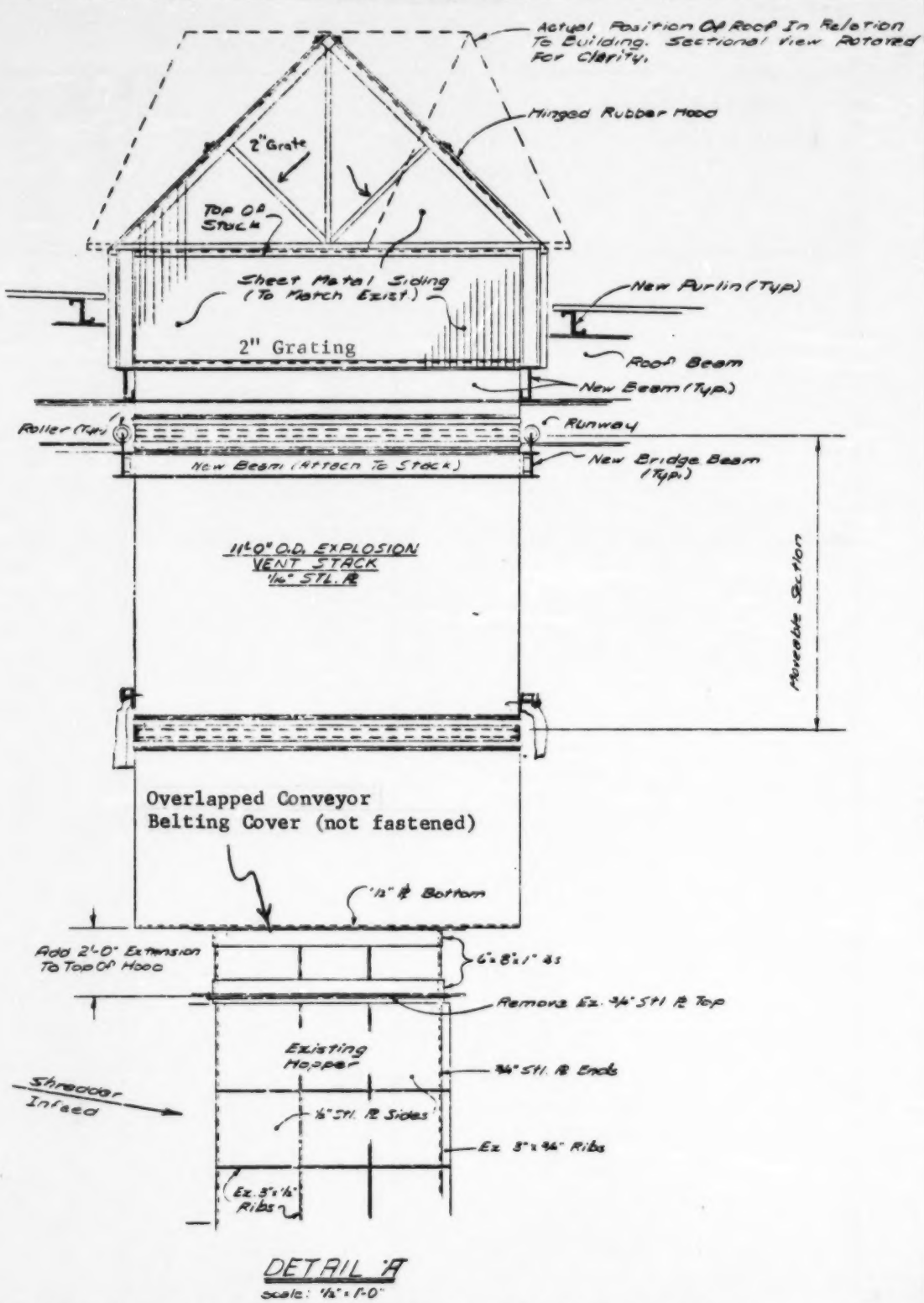
VENT COVERS

Vent covers are usually needed either (preferably) directly on the shredder or at the far end of the vent duct. Without these covers, dust and debris generated during the shredding process would be ejected and would possibly create a health and safety hazard to nearby personnel. Since impact forces from large ejected debris could prematurely open the vent cover, deflection gratings are often employed to rebound these missiles back into the mill. Figure A-3 is a drawing of the top of a vent duct covered by explosion vents which in turn are shielded by deflection bars.

The opening pressure of the vent cover should be low in comparison to the shredder structural damage threshold, $P_M$. Based on the explosion tests in the mock shredder, it is recommended that the static deployment pressure be no more than $P_M/5$ since the cover will open at a somewhat higher pressure under rapid explosion loads than under static test conditions.

Several different types of vent covers can be utilized. Some of the simplest covers consist of rubber flaps on the vent duct outlet. Rain hoods situated at least one vent duct diameter from the end of the duct are also effective in conjunction with a deflector grating inside the duct. On the shredder itself, commercially available explosion release doors and panels are sometimes used (see Reference A-3, pp 100-101). Vent cover construction and release mechanisms are described in the NFPA Explosion Venting Guide (Reference A-5, pp 89-93).

If explosion vent panels or doors are utilized, they should satisfy several criteria in addition to the vent area and release pressure criteria cited previously. First, vent panel/door inertia should be as low as possible, so as not to obstruct the open vent. NFPA 68[A-5] specifies that the vent panel weight be less than 2 lb/ft$^2$ (10 kg/m$^2$), while Bartknecht states (Reference A-3, p 101) that the panel weight should not exceed 1.2 lb/ft$^2$ (6 kg/m$^2$). Another important factor is that a rugged and shock resistant hinge or cable is required to prevent the panel/door from flying off during




DETAIL 'A'

Scale: 1/2" = 1'-0"

**Figure A-3. Explosion vent stack retrofitted onto shredder inlet hood**

explosions. Finally, there is a need to periodically check the vent actuation mechanism so that it can be relied upon when needed. Ahlberg and Boyko[A-4] report that their explosion doors did not deploy at all during two separate shredder explosions involving major damage. Therefore, an inspection and preventive maintenance program is recommended.

## BLAST WAVE PRESSURES OUTSIDE SHREDDER

During an explosion, flame and potentially damaging blast waves propagate out from the shredder explosion vent and from the inlet and discharge openings. Blast wave pressures can be estimated from the following hypothesized generalization of the data of Butlin and Tonkin[A-6]. Thus, the peak overpressure, $P_d$, at a distance, d, directly ahead of the vent/opening is given by

$$\frac{P_d}{P_M} = \frac{k}{k + d/\sqrt{A_v}} \qquad \text{(A-2)}$$

where

$P_M$ = maximum pressure in shredder (as used in eq (A-1) also);
$A_v$ = area of shredder vent or other opening closest to target structure;
$k$ = constant ≈ 1.7.

The value of k is probably dependent upon gas composition and shredder volume. The suggested value of 1.7 is based on test data[A-6] for methane-air explosions in a 28 $m^3$ (1,000 $ft^3$) enclosure.

Blast pressures exerted on a target located at some angular displacement from a line perpendicular to the vent opening will probably be somewhat less than given by eq (A-2) at the same distance, d. However, test data[A-2,6] are inconsistent as to how much of a reduction occurs. Therefore, a conservative approach would be to use eq (A-2) to estimate pressures at off-axis locations as well as in-line targets.

Adjacent structures vulnerable to blast waves include the shredder feed conveyor enclosure, the discharge conveyor, dust collection ducting, and the nearest building wall. As an example of the use of eq (A-2), consider the blast wave loading on the discharge conveyor for the same hypothetical 1,000 $ft^2$ shredder described previously. If the discharge conveyor is 4.5 ft below the 20 $ft^2$ discharge opening, the calculated value of $P_d/P_M$ is 0.63. Thus, the discharge conveyor could be subjected to a 6.3 psig blast loading, and should be strengthened accordingly to avoid damage.

## REFERENCES - APPENDIX A


1. Wiekema, B. J., et al. The Effects of Tubes Connected with Pressure Relief Vents. 2nd International Symposium on Loss Prevention and Safety Promotion in the Process Industries, DECHEMA, 1978, p. IV-223.

2. Hatwig, M. Selected Aspects of Explosion Venting," op. cit., p. IV-249, 1978.

3. Bartknecht, W. Explosions. Springler-Verlag, 1981, pp. 115-119.

4. Ahlberg, N. R. and B. I. Boyko. Explosions and Fires - Ontario Centre for Resource Recovery. Proceedings of ASME National Waste Processing Conference, May 1980.

5. NFPA 68. Explosion Venting 1978. National Fire Protection Association, Boston, Mass., 1978.

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# APPENDIX B

## VELOCITY MEASUREMENTS IN SHREDDER MOCK-UP

Hammermill-induced air velocities and flow rates in the shredder mock-up were measured by two different techniques: velocity probes and smoke injection.

### VELOCITY PROBE MEASUREMENTS

Velocity probe data were obtained in a horizontal cross-section 16 1/2 ft above the ground. Bidirectional low-velocity (pitot) probes (Figure B-1) were located at the center of the plane, and at a point 18 in. away from the wall on each face (see Figures B-1 and B-2). The probes were connected to a low-range Setra Model 239 pressure transducer. The potentiometer transducer, and power supply were housed in a temperature-controlled cabinet in order to minimize thermal drift and offset. Output from the transducer was connected to a strip chart recorder.

The test procedure was as follows. First, the transducer was connected to the pressure probe and the output recorded on the strip chart in order to obtain a zero flow reference level. After the mill was energized and allowed to reach full speed (900 rpm), recordings were taken for 20 sec to 1 min at each of the five probe locations. The mill was then shut down and coastdown was recorded in order to compare the final zero flow value with the initial zero value, i.e., to check for electrical drift in the transducer.

Transducer pressure data were converted to velocities at each of the test points. The resulting average velocities, peak fluctuating velocities, and turbulence intensities are shown in Table B-1. Average velocities range from 7 ft/sec upward to 8.4 ft/sec downward. Velocity profiles were then plotted as shown in Figure B-3. The data points were connected with straight lines and areas under the curve determined in order to obtain a cross-section averaged velocity. From this average velocity, a flow rate of 3800 cfm vertically upward was calculated.

### SMOKE INJECTION DATA

The flow rate obtained in the velocity calculations was compared to that obtained by a series of smoke injection tests. In each of these tests, a chemical smoke candle was ignited and placed in the operating shredder. The time from beginning of smoke discharge to maximum obscuration at the intake hood and discharge grating was measured. Similarly, upon exhausting the smoke bomb, the time from maximum smoke obscuration to virtual clearing of the shredder was measured. The time values were used to determine the flow rate in the following manner.

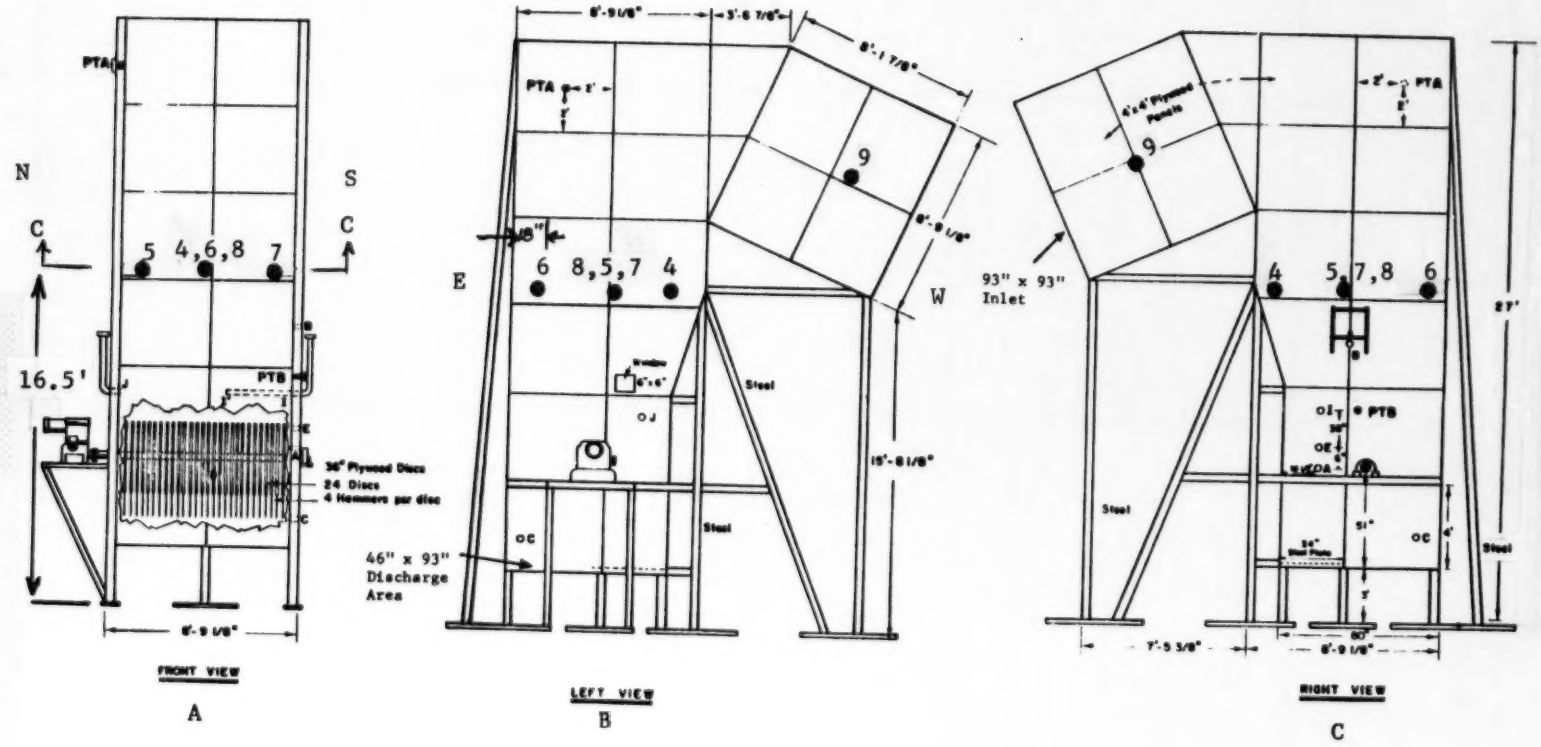


Figure B-1. Velocity Probe Positions in Shredder Mock-up
Note: Section View C-C is Shown in Figure B-2.

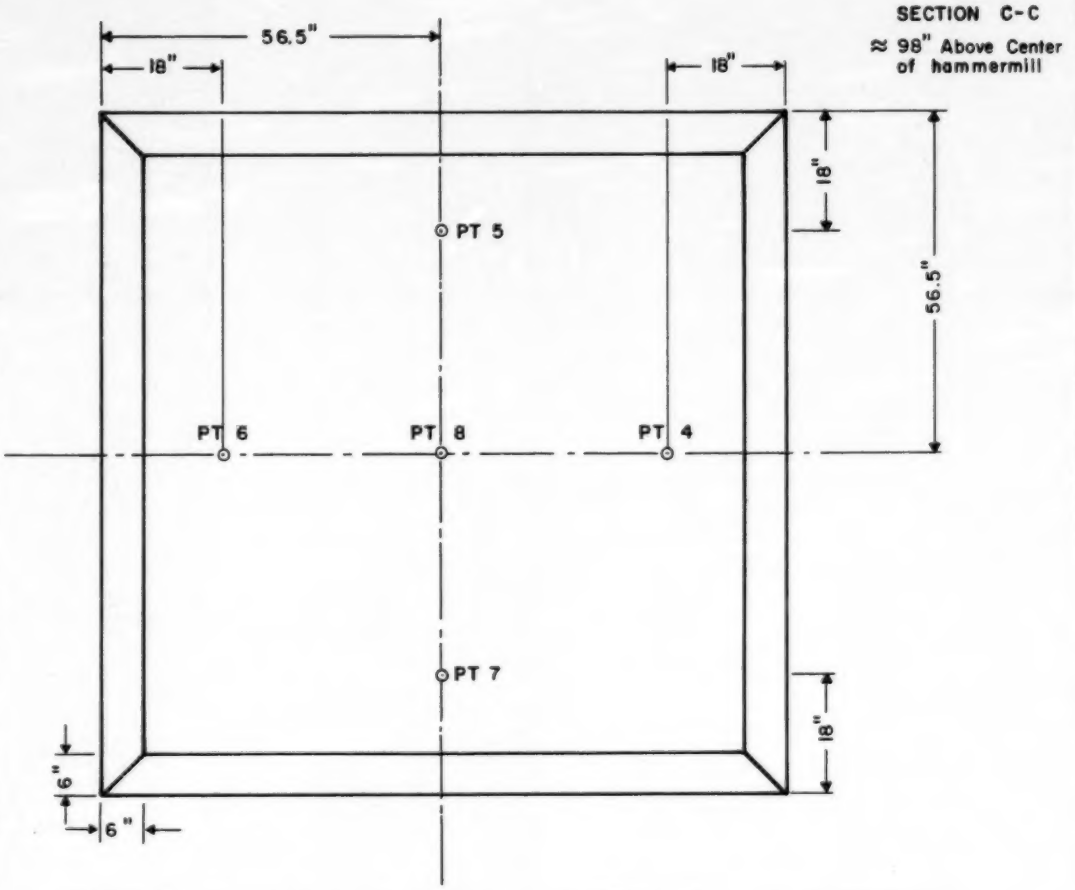


Figure B-2. Locations of the velocity probes

TABLE B-1. VELOCITY PROBE DATA

| Velocity Probe Location | Point | Velocity Max | Velocity Ave | Turbulence Intensity† |
|---|---|---|---|---|
| - | - | FPS | FPS | - |
| 18 in. from west wall | 4 | -9.3 | 0* | NA |
| 18 in. from south wall | 5 | +12.5 | +3.5* | 1.11 |
| 18 in. from west wall | 6 | +17 | +7.0 | 1.10 |
| 18 in. from north wall | 7 | +11 | +4.9 | 0.45 |
| Center of section C-C | 8 | -31 | -8.4 | 1.07 |
| Center of Intake Hood | 9 | -3.1 | -3.1* | - |

*These values are within the ±4 ft/sec accuracy of the pressure transducer

†Turbulence intensity = $\frac{\sqrt{u'^2}}{\bar{u}}$ where $\bar{u}$ = average velocity and u' = fluctuation relative to $\bar{u}$.

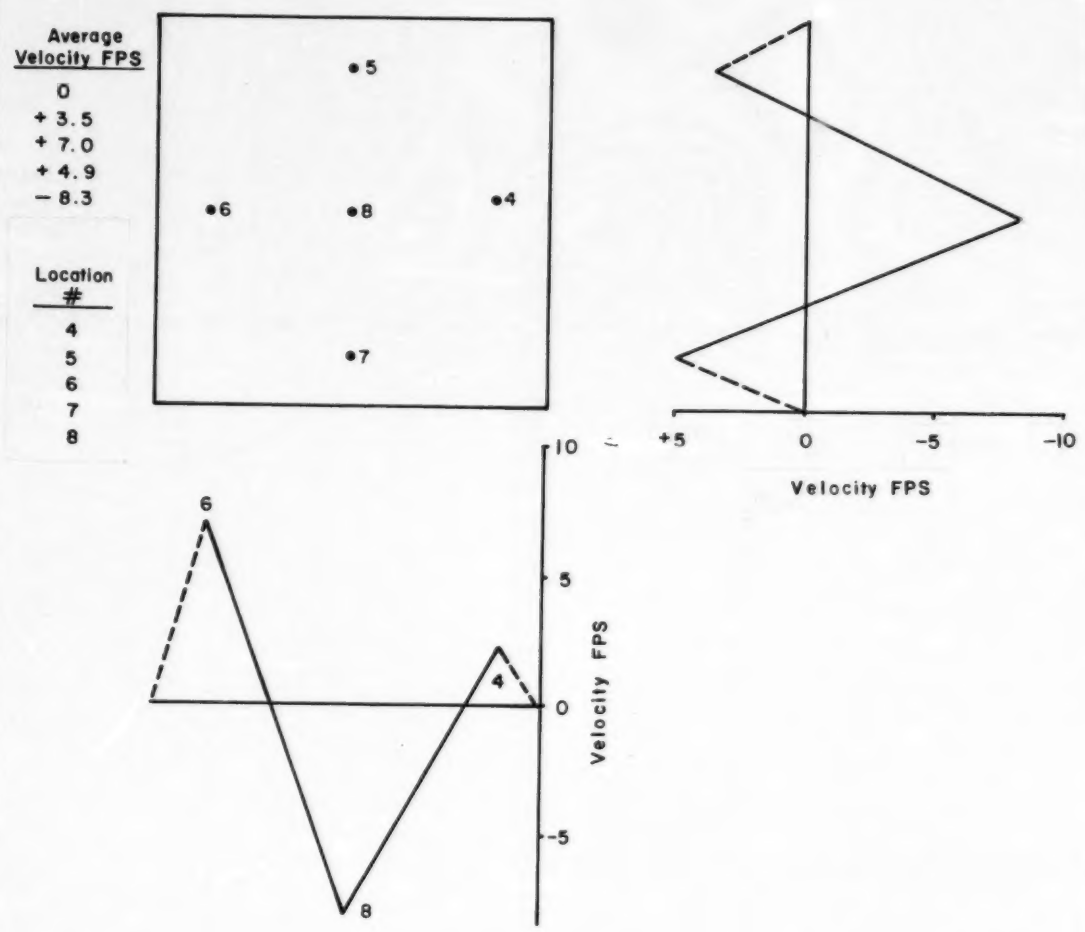


Figure B-3. Velocity profile

Assuming the smoke is uniformly mixed within the shredder, during smoke generation the concentration (C) at any time (t) is given by eq (B-2)

$$C = \frac{Q}{V}\left[1-e^{\frac{-(t - t_s)\,\dot{v}}{V}}\right] \qquad \text{(B-1)}$$

where

C = smoke concentration ($lb/ft^3$)
Q = smoke generation rate (lb/sec)
V = volume of the shredder (2200 $ft^3$)
$\dot{v}$ = flow rate through the shredder ($ft^3$/sec)
$t_s$ = time at start of smoke generation

If we consider the shredder to be "completely filled" with smoke when $C = 0.90\,\frac{Q}{V}$,

$$0.90\,\frac{Q}{V} = \frac{Q}{V}\left[1-e^{-\frac{(t - t_s)\dot{v}}{V}}\right] \qquad \text{(B-2)}$$

or

$0.10 = e^{-\frac{\Delta t\,\dot{v}}{V}}$, where $\Delta t$ = time interval required to "fill" shredder with smoke.
Thus

$\frac{\Delta t\,\dot{v}}{V} = -\ln(0.10) = 2.30$ and the ventilation rate is given by

$$\dot{v} = \frac{2.30\,V}{\Delta t} \qquad \text{(B-3)}$$

A similar calculation can be made using the time between maximum smoke density and 10% of maximum smoke density once the smoke bomb has exhausted itself.

In addition to providing total air throughput data, the smoke visualization tests allowed one to observe the magnitude of direction of flow and the degree of turbulence produced at various locations in the shredder.

Smoke bombs were placed in four separate locations in sequential tests as noted below and shown in Figure B-4:

1) at the center of the intake hood ($s_1$);
2) 3 ft above the horizontal center; on the vertical center in the intake hood ($s_2$);
3) at the northwest corner of the discharge grate ($s_3$); and
4) at the southeast corner of the discharge grate ($s_4$).

Observation of the smoke discharge in these tests indicated the following:

1) Maximum obscuration occurred 75 sec to 90 sec after ignition of the smoke bomb, regardless of location;

2) Air flow velocity and turbulence level in the intake hood area are extremely low. Smoke drifted about in this area with no definite overall velocity either into or out of the shredder; and

3) The majority of the smoke generated below the hammermill exits through the discharge grate within 2 min. Very little (~20%) smoke is carried upward to exit through the intake hood.

The conclusions reached are:

1) The turbulence in the shredder is produced primarily by rapidly agitating the enclosed air and that surprisingly little air is forced through the shredder due to the action of the hammermill;

2) Based on eq (B-3) and the observed smoke obscuration times of 75-90 sec, the air throughput rate ranges from 3380 CFM to 4050 CFM. Air flow is directed from the discharge grate, through the hammermill and out of the intake hood; and

3) These observations are in agreement with the data collected with the velocity probes, which indicated a highly turbulent, nonuniform velocity distribution with a net air flow rate of about 3800 cfm directed out through the intake hood.

REFERENCES

B-1 Heskestad, G. A Robust Bidirectional Low-Velocity Probe for Flame and Fire Application. Combustion and Flame, 1976, Vol. 26.

B-2 Baturn, V. V. Fundamentals of Industrial Ventilation, Third Edition, Pergamon Press, 1972, p. 35.